An indeterminacy-based ontology for quantum theory

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Abstract

I present and defend a new ontology for quantum theories (or "interpretations" of quantum theory) called Generative Quantum Theory (GQT). GQT postulates different sets of features, and the combination of these different features can help generate different quantum theories. Furthermore, this ontology makes quantum indeterminacy and determinacy play an important explanatory role in accounting for when quantum systems whose values of their properties are indeterminate become determinate. The process via which determinate values arise varies between the different quantum theories. Moreover, quantum states represent quantum properties and structures that give rise to determinacy, and each quantum theory specifies a structure with certain features. I will focus on the following quantum theories: GRW, the Many-Worlds Interpretation, single-world relationalist theories, Bohmian Mechanics, hybrid classical-quantum theories, and Environmental Determinacy-based (EnD) Quantum Theory. I will argue that GQT should be taken seriously because it provides a series of important benefits that current widely discussed ontologies lack, namely, wavefunction realism and primitive ontology, without some of their costs. For instance, it helps generate quantum theories that are clearly compatible with relativistic causality, such as EnD Quantum Theory. Also, GQT has the benefit of providing new ways to compare and evaluate quantum theories.

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1. Introduction

What exists at the fundamental level according to our best scientific theories? Or, more concretely, what is the right ontology behind the puzzling phenomena represented by quantum theory (QT), arguably our most widely applicable fundamental theory? It's unclear how to understand and answer satisfactorily these questions. There are several interpretations of QT, or more accurately, different quantum theories (QTs). Also, there are longstanding foundational and philosophical issues surrounding the elements of the theory, such as the wavefunction or quantum state. To address these questions, there are diverse, what I will call ontological frameworks that provide clear ontologies applicable to various quantum theories. A widely debated framework is Wavefunction Realism,[2] which considers that what fundamentally exists is a wavefunction living in a large multidimensional configuration space. Another widely debated framework, called primitive ontology,[3] typically considers that quantum states/wavefunctions/density operators have a nomological character. Moreover, the primitive ontology that these objects describe/govern concerns entities with determinate features that live in a determinate location of the three-dimensional space. Other alternatives consider that the density operator is a property of spacetime points,[4] etc. Since we currently don't know what the right QT is, a plausible strategy to investigate its ontology is to formulate and analyze ontological frameworks, which, given their generality and clarity, will likely provide that information.

What the current major ontological frameworks have in common is that they consider that there are determinate properties or features or laws or fields (e.g., wavefunction, primitive ontology, etc.) that are fundamental and play a key explanatory role. Indeterminate properties, in a sense that will be clarified, arise from them and have a secondary explanatory role. For instance, according to wavefunction realism, indeterminate properties arise from a multidimensional field, and what plays a key explanatory role is this field.[5] However, historically, the so-called Eigenstate-Eigenvalue Link (EEL) played an important role in interpreting QT, especially within the more "orthodox" interpretations.[6] According to this link:

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[2] Albert (1996, 2023), Ney (2021).
[3] See, e.g., Allori (2013), Dürr et al. (1992), and Goldstein & Zanghì (2013).
[4] Wallace & Timpson (2010). See also, e.g., Myrvold (2022) and references therein.
[5] See also Glick (2017).
[6] See Gilton (2016) for a historical overview of the importance of this link.

A system S has a determinate value q of an observable O if and only if the quantum state of S is in eigenstate of O with an eigenvalue q.

This link often leads to the assumption that if the quantum state of S is in a quantum state that is not an eigenstate of some observable, the system has, in a sense, an *indeterminate value* of that observable. It also has led to the view that QT presents a new kind of indeterminacy, an ontological indeterminacy.[7] The source of this indeterminacy is not in our knowledge or the semantics of our language[8] but in the world itself. However, despite this link's importance, an ontological framework applicable to the major quantum theories where quantum indeterminacy plays an important explanatory role hasn't been proposed and defended.

I propose and defend an alternative ontological framework, called generative quantum theory (GQT). In this framework, quantum indeterminacy plays an important explanatory role rather than the opposite, reversing the arrow of explanation from what is typically proposed by the ontological frameworks of QT. I will compare GQT to the most widely discussed ontological frameworks, wavefunction realism and primitive ontology, and explain that it doesn't suffer from some of their notorious costs while proving some important benefits.

The rough idea of GQT is that the world is constituted by default by entities with so-called *indeterminate (value) properties*, which give rise to entities with *determinate (value) properties*. GQT will also offer the possibility of giving rise to quantum theories where entities with determinate value properties also exist by default, along with entities with indeterminate value properties.[9] Via a relation between determinate and indeterminate value properties and other features of systems, I will also provide a new analysis of quantum indeterminacy and determinacy. Furthermore, contrary to the previous ontological frameworks, this framework postulates different sets of features. In this article, I will propose seven different but interrelated features. The combination of these different sets can help generate different quantum theories, which, as I will argue, will provide several benefits.

Often associated with Wavefunction Realism and Primitive Ontology is a reificatory view of the wavefunction or a literalist reading of it either as a law or an object.

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[7] See, e.g., Barnes & Williams (2011), Calosi & Wilson (2019), Lewis (2016).
[8] See, e.g., Fine (1975) or Williamson (1994).
[9] Such as Bohmian mechanics, as we shall see.

GQT will adopt a different view of quantum states/wavefunctions and density operators,[10] assigning them various roles. They will allow for inferences about and representation of the different possibilities of determinate values arising. Also, they help represent the so-called *quantum properties* of systems that are related to value properties, "giving rise to them." However, this representation won't be a literalist or *self-standing* one. Quantum states have the support of values, observables and other tools, such as directed graphs, DAGs (directed acyclic graphs, i.e., directed graphs with no cycles), and Quantum Causal Models, to make inferences and represent the various features mentioned above. Importantly, and this is a key innovation, these tools will support inferences and representations about structures of interactions that give rise to determinacy.[11] Different QTs will appeal to different structures of this kind. Given their epistemic role, quantum states of a system won't collapse in a physical sense during interactions. There is instead a state update of the original state of a system that can be implemented, for example, upon its decoherence, specific interactions, under collapse, branching, etc. I will argue that this view on the nature of quantum states is less problematic than the one adopted by WR and PO.

I will start by presenting the basics of GQT via the Ghirardi-Rimini-Weber (GRW) theory (section 2.1). Then in the rest of section 2, I will present the Many-Worlds Interpretation (MWI), relationalist single-world, and Bohmian Mechanics versions of GQT.[12] Finally (section 2.4), I will show how GQT allows us to move beyond the standard interpretations by generating a local QT called Environmental Determinacy-based Quantum Theory (EnDQT).[13] I will also show how GQT applies to hybrid classical-quantum theories.[14] I will then compare GQT with wavefunction realism and the primitive ontology framework and argue that it provides important benefits that these views don't provide, and without some of its costs (section 3). Also, I will argue that it allows us to make a new comparison between quantum theories and argue that EnDQT should be preferred in a certain sense.

According to GQT, systems can occupy spatiotemporal regions (ST version) or give rise to spacetime (non-ST version) using an appropriate theory of quantum gravity. I will focus on the ST version for simplicity, but spacetime regions aren't necessarily

[10] Note that I will often refer to density operators as quantum states.
[11] See section 2.4.
[12] See, e.g., Wallace (2012), Goldstein (2021), Ghirardi & Bassi (2020) and references therein.
[13] Pipa (2023).
[14] E.g., Oppenheim (2023), Diósi (1995).

fundamental in this view. To simplify, I will mainly assume non-relativistic QT and the Schrödinger picture Hilbert space-based finite-dimensional QT in the presentation of the theories.[15] However, I will have something to say about the quantum field theoretic case in section 2.4. Furthermore, note that given the non-reificatory approach to quantum states, viewing it as only as an auxiliary tool, GQT doesn't rely on a particular mathematical formulation of QT, and it can be expressed in terms of other formulations.[16]

2. Some generative quantum theories based on quantum properties

I will start presenting a generative version of GRW, which I will call generative-GRW. This theory will serve to explain in the following order the basic features assumed by GQT: generators, generative properties, the kinds of determinate values that generators generate, the ontology of properties adopted, the conditions that establish how generators account for determinacy, and two structural features that help explain how determinacy arises via interactions.

2.1. A generative collapse theory and introduction to GQT

We can characterize the role of any "interpretation" of QT or QT as giving an account of how systems end up having determinate values, although, given the EEL, unitary interactions leave such values indeterminate.

To give a general account of how systems come to have determinate values, GQT introduces generator systems of determinacy or *generators*. Note that the word "generate" will be used in two different senses. It will be used to designate how GQT allows for different QTs to be built, and how some elements of GQT give rise to determinacy. Generators are systems that have the capacity to give rise to other systems having determinate values. *Non-generator systems* don't have the capacity to give rise to other systems having determinate values. Also, we have *generative properties*, which are the properties that generators have via which they influence other systems to have determinate values. A key claim of GQT is that each QT introduces different generators and generative properties, which generate different kinds of determinate values.

[15] See, e.g., Barrett (2019) for an introduction.
[16] Such as the Heisenberg picture, interaction picture, and the Lagrangian formulation.

Generators and generative properties are two interrelated features that help generate quantum theories. As it will become clearer, in the case of generative-GRW, the generators are the systems that have positions, and some of their positions are generative properties.

The determinate values that each generator generates is another feature that helps generate quantum theories. The determinate values generated by generators can be absolute (i.e., don't vary according to systems), relative to a system (for system X, system Y has a determinate value v, but for system Z, Y has a value v' or an indeterminate value), relative to multiple copies of systems (multiple copies of the same interacting systems arise, each with different possible determinate values like in the MWI), etc. Unless stated otherwise, I will consider the determinate values generated as absolute, although in the next section, we will see other possibilities.

GQT, in principle, allows for multiple ontologies of properties, and this is another one of the features that help generate quantum theories. Different ontologies of properties can, in principle, be adopted (see section 4). In this paper, I will propose and focus on an ontology of properties where it's manifest when systems, interacting with other systems S, have the properties that give rise to S having a determinate value, i.e., it becomes manifest when they have generative properties.

According to this ontology, for GRW and GQT in general, systems are collections of quantum properties, and value properties (henceforward, values) are related to quantum properties (more on this below). To explain what quantum properties are, first note that I will view GRW as considering that there are fundamental quantum systems called particles where a particle is a system having position quantum properties (and the associated momentum quantum properties) and other quantum properties (e.g., spin in different directions, energy, etc.). We consider that particles have different subsystems, each a collection of certain quantum properties. Only one of the systems has position quantum properties (alongside momentum and energy), and the other systems have other quantum properties, such as spin and energy. The former system, as I have mentioned above, is a generator. It is a generator because it has the capacity to give rise to other systems having determinate values (having generative quantum properties). This contrasts with the subsystem of the particle that has spin quantum properties, which isn't a generator. Quantum properties of subsystems of particles are represented via quantum states belonging to different Hilbert spaces and self-adjoint operators (which I will call observables) that act on those spaces.

Quantum properties have a feature called *differentiation*, which impacts the determinacy of the values that systems having those properties give rise to. Interactions with generators change the degree of differentiation of a quantum property that a target system and the generators have (we will see further below why differentiation comes in degrees). More concretely, the differentiation of a quantum property that a target system S might end up with due to an interaction with generators can be inferred and measured via the distinguishability of certain quantum states of the generators concerning the quantum states of S (hence the use of the term differentiation). Furthermore, the quantum states of S are eigenstates of an observable that also represents that property.[17] When such differentiation is *maximal* and *stable* (in a certain sense to be defined soon), I consider that we end up having S with that quantum property *stably differentiated*, and S will have a determinate value related to that quantum property. Crucially, generators under interactions with S will also have a quantum property stably differentiated, and thus a determinate value, when they give to S having a stably differentiated quantum property (again, to some degree at least, as we shall see). This quantum property of the generators is a *generative quantum property*. So, for GQT

All generative quantum properties of a (generator) system are (fully) stably differentiated.

Note that not all stably differentiated quantum properties are generative. Spin quantum properties in different directions in GRW are never generative. It's the subsystem of the particle that has certain positions that gives rise to other systems having a determinate value, not the subsystem that has spin.

As we will see, the use of the term *stable* is because the process that allows us to infer if there is determinacy will often involve, via decoherence, the analysis of a certain quantity that should assume a stable value over time, i.e., the distinguishability/differentiation of the quantum states of an "environmental system" interacting with a target system. So, I will consider that the stabilization of the differentiation of a quantum property of a target system S in most quantum theories arises via a *stable quasi-irreversible* or *irreversible process* that gives rise to and fixes the determinacy of the value in some degree proportional to the degree of differentiation of the quantum property that S has at some time t. More concretely, this process leads S to

[17] Or improper eigenstates in the non-idealized case of systems whose quantum properties are represented via infinite-dimensional Hilbert spaces, such as position quantum properties. See, e.g., Wallace (2019).

have a quantum property D*-P with a degree of differentiation D* to give rise to a value of P (e.g., spin in different directions, position, etc.) with a degree of determinacy D=D* at t. I will call the process in which a generator system S', having a generative quantum property, gives rise to other systems S having a stably differentiated quantum property, a *process of stable differentiation* or the stable differentiation of quantum properties of S by S'.

In generative-GRW, this process is the process of collapse or spontaneous localization. It leads systems to have a stably differentiated quantum property and, thus, a determinate value. In the MWI and EnDQT this process is a quasi-irreversible and irreversible process, respectively, represented via decoherence. In the former case, it is called the process of branching into different worlds.

Let's turn to further details of this view. I will consider that

Unless stated otherwise, in the absence of interactions or other processes that lead to a process of stable differentiation, quantum properties of systems will be undifferentiated, which means having the lowest degree of differentiation. So, some interactions or processes change the differentiation of the quantum properties that systems have.

Thus, indeterminate values/undifferentiated quantum properties are the default features of systems. Only under certain processes and interactions do systems having determinate values arise. It is in this sense that for GQT, quantum indeterminacy plays an important explanatory role, being an important tool to interpret quantum theories: it establishes when determinacy doesn't arise, being a default feature of systems. The exceptions in this article are Bohmian mechanics, where some systems have always determinate values of position, and hybrid classical-quantum theories, which will have, for example, the metric and its conjugate momentum always stably differentiated. In the case of these two theories, having determinate values or indeterminate values are both default features of systems.

Note that, perhaps, one may consider the (typically regarded) non-dynamical quantum properties (e.g., electric charge, mass) to be also stably differentiated by default. However, the QTs investigated here can assume that "non-dynamical" observables represent undifferentiated quantum properties that become stably differentiated under interactions with the typical appropriate environments. Although this is not mandatory when adopting GQT, for simplicity, I will assume this in this article.[18]

Stability conditions are the conditions under which a system comes to have a stably differentiated quantum property or (more generally) a determinate value, and they are another feature that helps generate quantum theories. Stability conditions for generative and non-generative quantum properties may differ in the case of the theories explained in this article, and to summarize, they are the following,

A system S has a stably differentiated quantum property, giving rise to S having a determinate value associated with that property when,

i) if that quantum property is a generative one (which only generators have), S has that stably differentiated quantum property due to a spontaneous chancy collapse process (GRW), due to or in certain interactions (MWI, single-world relationalist views, and EnDQT), or S has by default that quantum property stably differentiated (Bohmian mechanics and hybrid classical-quantum theories); or
ii) if that quantum property isn't a generative one, S is interacting with generators that have a generative quantum property, which gives rise to S having that stably differentiated quantum property.

Regarding i), for example, Bohmian mechanics considers that the position quantum properties of systems are always stably differentiated by default and those are the generative quantum properties. GRW considers that generators can be subject to collapse, which gives rise to systems having stably differentiated position quantum properties independently of the interactions they have with other systems, going from having an undifferentiated position to a stably differentiated one. More concretely, systems in GRW often evolve unitarily; however, they have the probability per unit time λ of indeterministically being localized, *collapsing*, and having at least a stably differentiated and determinate value of position. Note that I don't mean that collapse

[18] Decoherence was proposed to account for such so-called superselection rules (see, e.g., Earman (2008) and Giulini et al. (1995)) So decoherence by an appropriate environment could be used by at least for some QTs to represent and infer such interaction. I will assume that other QTs that don't crucially rely on decoherence, such as GRW and Bohmian mechanics, can invoke decoherence by systems with the quantum property position to explain such superselection.

refers to the wavefunction but the stable differentiation process involving systems since the wavefunction here is not considered a real entity.

The collapse of a system S_i in a spacetime region is represented via the multiplication of the total wavefunction written in the position basis by a narrow Gaussian wave packet in the position basis whose width is σ, which represents the localization accuracy. Moreover, the probability of the wavepacket being centered in region C is given by the Born rule. The stably differentiated quantum property of the generator system S_i affected by collapse is represented by the post-collapse wavefunction[19] plus the observable position that acts on the Hilbert space of system S_i. The possible determinate values of S_i are represented by the eigenvalues of the observable that the position quantum states of S_i are eigenstates of.[20]

Regarding ii), generative-GRW also considers that when a generator or non-generator target system S interacts with a certain generator system or systems S', so that they get *entangled*[21] and a collapse happens, this leads to the stable differentiation of the quantum properties of S by S'. More precisely, we can infer that there is an interaction that involves generators S' having a generative quantum property, which leads the target system S to have a determinate value. The stably differentiated quantum property of the target system will be represented by the eigenstates of the observable concerning a property (spin in different directions, etc.) that are correlated with the position states of the generator or generators upon collapse plus that observable.

As I have said above, the full distinguishability of the quantum states in a superposition of the generator or a collection of generators constituting system S' concerning the quantum states of the target system S (which could be a generator or not) *just before* collapse (or another process of stable differentiation in the case of other QTs) allows us to infer which stably differentiated quantum property S will have due to S' after a certain time. These quantum properties often go beyond position and can be energy, spin in a direction, etc.

In the case of generative-GRW, the stable differentiation of a quantum property of a target system (i.e., a system under analysis by a model) can be inferred via the quasi-

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[19] Given that the quantum state has an inferential role, I will accept the standard assumption that we can ignore the global phases of the quantum state to make inferences about and represent properties.

[20] Due to the continuous spectrum of the position observable, it brings some extra complications. However, given our finite-dimensional Hilbert space idealization, I will neglect them. See, e.g., Wallace (2019) for ways of dealing with it. Also, the wavefunction leaves some "tails" upon collapse, assuming the representational and inferential role of the quantum states assumed by GQT, the approximate ways of representing determinate values aren't a problem for this view (more on this below).

[21] I will make precise below the interactions represented via entanglement.

irreversible process of decoherence of the target system by its environment composed of many generators, and which occurs just before collapse. This is because quasi-irreversible decoherence will typically require many environmental systems having a position (which is correlated with the position of the others) to be stably entangled over time with the target system. So, very likely, some will collapse, triggering a collapse process that leads the others within that environment to have a determinate value due to their correlations, as well as the target system. More on this process below.

Relatedly, it is plausible to consider that at least some quantum properties can be stably differentiated in terms of different degrees, and this impacts the subsequent *degree of determinacy* that arises from those quantum properties. For example, in the double-slit experiment, if the detectors at the slits interact with a quantum system weakly, in such a way that we can't fully distinguish in which slit it passed, we get some disappearance of interference. These interactions will give rise to a low entanglement between the position and the degrees of freedom of the detector. Furthermore, the more the interactions between the target system and the detector distinguish the path of the system, the more entanglement we have between the position of the target system and the degrees of freedom of the detector, and the more the interference tends to disappear until it disappears completely under maximal entanglement. So, I will consider that quantum properties come in terms of different *degrees of (stable) differentiation*, as well as the determinacy of the resultant values.

For example, a system can have different quantum properties spin-x with different degrees of differentiation over time. Values come in terms of degrees of determinacy D and depend on the degree of differentiation D* of quantum properties. A quantum property is undifferentiated when it has the lowest degree of differentiation and differentiated when it has the highest one. A value with the maximum degree of determinacy is a determinate value, and with a minimum degree of determinacy is an indeterminate value.[22]

I will now show more concretely how we can infer the degree of differentiation of the quantum property that a system, after interactions, ends up with via the degree of entanglement of its quantum states with its environment and decoherence.

The degree of differentiation of a quantum property of a system can be measured via the non-diagonal terms of the reduced density matrix of the system subject to

[22] Remember that this assumption is not mandatory when adopting since GQT allows for different property ontologies.

decoherence when we trace out the degrees of freedom of the environmental systems that are interacting or interacted with the system of interest. Let's consider a toy scenario with system E, which is a generator, constituted by many subsystems that interacted or are interacting with system S. For instance, suppose S has quantum properties spin in different directions that are interacting strongly (i.e., the Hamiltonian of interaction dominates the system's evolution in the timescales of interest) with many systems with positions, which constitute E.[23][24] For simplicity, throughout this article, I will assume this kind of evolution of the system under the interactions that lead to decoherence.[25] Let's assume some situations where S has initially an undifferentiated spin-z quantum property. S then interacts with E, and their interaction is represented via the standard von Neumann interaction at least approximately as $|\uparrow_z\rangle_S|E_0(t)\rangle_{E\,DS} \rightarrow |\uparrow_z\rangle_S|E_\uparrow(t)\rangle_{E\,DS}$, $|\downarrow_z\rangle_S|E_0(t)\rangle_{E\,DS} \rightarrow |\uparrow_z\rangle_S|E_\downarrow(t)\rangle_{E\,DS}$, or as

$$(|\uparrow_z\rangle_S + |\downarrow_z\rangle_S)|E_0(t)\rangle_{E\,DS} \rightarrow \alpha|\uparrow_z\rangle_S|E_\uparrow(t)\rangle_{E\,DS} + \beta|\downarrow_z\rangle_S|E_\downarrow(t)\rangle_{E\,DS}. \quad (1)$$

The change of the degree of differentiation of the quantum property spin-z of S upon this interaction can be inferred and calculated through the reduced density operator $\hat{\rho}_S(t)$, which is obtained by doing the partial trace of the degrees of freedom of the environment. More concretely, this analysis is done through the overlap terms that concern the distinguishability of the states of E with respect to the spin-z of S, i.e., $\langle E_\uparrow(t)|E_\downarrow(t)\rangle_{E\,SS}$ and $\langle E_\downarrow(t)|E_\uparrow(t)\rangle_{E\,DS}$. More generally, consider a system S that initially has an initially undifferentiated quantum property D*-P, where the observable that concerns P has eigenstates $|s_i\rangle_S$. Given the interaction between S and environmental system E, after tracing out the degrees of freedom of E, we obtain that

[23] Alternatively, in other quantum theories that don't privilege position, we could consider instead an environment with systems with spin in multiple directions. See, e.g., Cucchietti et al. (2005).
[24] Realist decoherence models involving environments with position quantum properties include, for example, collisional models of decoherence and models of quantum Brownian motion. See, e.g., Joos & Zeh (1985), Kiefer & Joos (1999), Schlosshauer (2007) and references therein.
[25] More complex models of decoherence (see, e.g., Zurek, 2003) where the systems don't interact strongly with the environment, which involves the self-Hamiltonian having more weight on their evolution, may give rise to different observables with determinate values depending on the initial quantum states. More on this below.

$$\hat{\rho}_S(t) = \sum_{i=1}^{N} |\alpha_i|^2 |s_i\rangle_S\langle s_i| + \sum_{i,l=1,i\neq l}^{N} \alpha_i^*\alpha_l |s_i\rangle_S\langle s_l|\langle E_i(t)|E_l(t)\rangle_{E\,DS} + \alpha_l^*\alpha_i |s_l\rangle_S\langle s_i|\langle E_l(t)|E_i(t)\rangle_{E\,DS}. \quad (2)$$

Then, a measure of the degree of differentiation of the quantum property D*-P of S in the spatiotemporal region ST for the simple scenarios that we are considering will be given by the von Neumann entropy[26] $S(\hat{\rho}_S(t))$ of $\hat{\rho}_S(t)$ over lnN, where N is the number of eigenvalues of $\hat{\rho}_S(t)$,

$$D^*(P,S,ST,t) = \frac{S(\hat{\rho}_S(t))}{lnN}. \quad (3)$$

If $D^*(P,S,ST,t)$ via the above overlap terms goes quasi-irreversibly, *i.e.*, *stably*, to one over time (in the sense that the recurrence of this term back to not being significantly different from zero is astronomically large), and these interactions involve many environmental systems that make this process hard to reverse, it is considered that S is decohered by E. In the QTs that appeal crucially to decoherence to infer when systems have determinate value, such as the MWI (section 2.2) and EnDQT (section 2.4), it is inferred that when decoherence occurs, S has a *stably* differentiated quantum property, having a determinate value due to E (but with some caveats in the case of EnDQT). More precisely, we can infer from this process that E also has a stably differentiated quantum property/generative quantum property, which leads S to also have a stably differentiated quantum property.

Upon knowing the actual result, we update the state of S to one of the $|s_i\rangle_S$, and consider that the system has a determinate value, which is an eigenvalue of the observable that $|s_i\rangle_S$ is an eigenstate of. Similarly, for E, where its possible determinate values will be the eigenvalues of the observable that $|E_i\rangle_E$ are eigenstates of. In the language typically employed by decoherence theorists, $|s_i\rangle_S$ for each i are pointer states, and the observable that these states are eigenstates of is the pointer observable "selected" by the environment

[26] Given a density operator ρ_S for quantum system S, the von Neumann entropy is $S(\rho_S) = -tr(\rho_S ln\rho_S)$. $S(\hat{\rho}_S)$ is zero for pure states and equal to $ln\,N$ for maximally mixed states in this finite-dimensional case.

E.[27] In GRW, also taking into account the account the collapse laws, we can infer there will be a collapse to when this occurs with an environment constituted by systems with the quantum property position. However, the collapse timescale is typically longer than the decoherence timescale.[28]

More generally, we can measure and represent the degree of differentiation D* of the quantum property D*-P that S will end up with at the end of the interaction with E at t, with $0 \leq D^{*}(P, S, ST, t) \leq 1$, in the possible elements of the set of spacetime regions ST where S is differentiated by E. At least in the case of the MWI and EnDQT, we can also infer the differentiation timescale, which is equal to the decoherence timescale. This is done by analyzing the value in which $D^{*}(P, S, ST, t)$ stably converges over time.

Thus, note that, as I have mentioned, a quantum property of S might not be fully stably differentiated and just be *stably differentiated* to some degree D* by E, and thus, it gives rise to a value with a degree of determinacy D = D*. This happens if the above quantum states of the environment have a certain *stable* non-zero overlap over time (notice how stability plays a role in these inferences). So, it is considered that in order for generators to have a generative quantum property and hence give rise to this process, they need to give rise to a quasi-irreversible process, which involves many degrees of freedom of the environment, in such a way that they decohere the target system *to some degree*.

The decoherence in these scenarios gives rise to the following criterium: in order for system S to have a determinate value v of O_S, the observable O_S of S that is monitored by system E, and whose eigenstates are decohered by E in the sense above, has to at least approximately commute with the Hamiltonian of interaction H_{SE} representing the interaction between S and E, i.e., $[H_{SE}, O_S] \approx 0$. This is the so-called commutativity criterion.[29] v is among the possible eigenvalues of O_S.

We can use decoherence to represent quantum properties. The generative (stably differentiated) quantum property of the target system is represented by the quantum states in the superposition that are decohered by (or entangled with) the generator plus the observable that these quantum states are eigenstates of. The generative (stably

[27] Note that pointer states here don't necessarily refer to the quantum states of a measurement device, but whatever is the target system.
[28] See Bacciagaluppi (2020) and references therein for the relation between collapse theories, decoherence, and their timescales.
[29] See Schlosshauer (2007) and references therein. This criterion implies that all terms in a Hamiltonian of interaction will individually satisfy this criterion. In more complex models of decoherence where the Hamiltonian of interaction doesn't dominate the evolution of the systems, note that this monitoring may be indirect, such as the decoherence of momentum in more complex models of decoherence than the ones mentioned here (Zurek et al., 1993), where there is direct monitoring of the position. The latter is contained in the Hamiltonian of interaction of the system (but not the former), and that's why the decoherence of the momentum is indirect.

differentiated) quantum property of the generator is represented by the quantum states that decohere the quantum states of the target system to some degree and the observables that such quantum states are eigenstates of.

However, not all interactions with generators[30] give rise to systems having a determinate value, although there is something that changes in the quantum properties of the systems under these interactions. Consider the spin of a particle in different directions in a series of Stern-Gerlach devices without letting the particles hit a screen between each device. This leads the system S^* with a spin in a certain direction to interact with the generator S', leading to their entanglement. Assuming the GRW theory, there is something that changes in the spin direction of the quantum systems when they go from one magnet to the other, but (very likely) there is no collapse/stable differentiation. If there were, we would have an irreversible process, and thus, we wouldn't be able to reverse the result of the operations by having a Stern-Gerlach interferometer that reverses the state of the particle to its previous state. So, it's plausible to consider that the spin of the system that interacts with the generator has an indeterminate value, although there is something that changes in the quantum property that corresponds to that indeterminate value.

In most quantum theories presented here, the interactions that don't lead to stable differentiation, such as the one above, can be *inferred* and represented simply by the quantum states and observables in the models where we have entanglement between the degrees of freedom of interacting quantum systems,[31] or relatedly where we have the so-called virtual/*reversible* decoherence. This decoherence involves "entangling" interactions that are reversible, not giving rise to an irreversible or quasi-irreversible physical process, because often they don't involve enough environmental systems that make such process hard to reverse unitarily, and thus, it's not typically considered real/irreversible decoherence. In the case of GRW, this reversible process involves the entanglement between the quantum states of a small number of generator or generators S' in the position basis (the environment) and the generator or non-generator target system S^*.[32] Taking into account the collapse laws, since it doesn't involve sufficient systems to very likely collapse occur, it allows us to infer that stable differentiation likely

[30] Or, at least in the case of EnDQT and MWI, with systems that could end up being generators.
[31] QTs will often postulate different structures that establish when systems are interacting or not. I will come to that soon.
[32] See, e.g., de Oliveira & Caldeira (2006).

won't occur. In the Stern-Gerlach case above, we obtain that both systems, after interacting, are represented by

$$|\Psi(\mathrm{t}')\rangle = \frac{1}{\sqrt{2}}(|\uparrow_z\rangle_{S^*}|up\rangle_{S'} + |\downarrow_z\rangle_{S^*}|down\rangle_{S'}), \quad (4)$$

and the self-adjoint operators spin-z and position that act on the position and spin Hilbert spaces of S. So, via entanglement and reversible decoherence, we represent and infer those systems that have an undifferentiated quantum property in interactions with other systems, and thus, when generators don't have generative quantum properties.[33]

So, decoherence for GQT is regarded as an epistemic tool that can often be used to infer which systems have undifferentiated or stably differentiated quantum properties and to infer if they will give rise or not to stable differentiation and, therefore, determinacy through interactions. Equivalently, it serves as a tool to infer if generators will have a generative quantum property under interactions. Furthermore, for some QTs (such as in the MWI) decoherence also allow us to infer which systems are generators and have generative quantum properties. Some factors will need to be taken into account in the use of decoherence as an inferential tool, some of them already mentioned above, but I want to emphasize them.

It requires an analysis to distinguish if we have a reversible or irreversible process of decoherence. This analysis largely appeals to pragmatic factors such as the number of systems that interact with the target system. It is also necessary to analyze the quantum properties of the systems of the whole environment that interact with the target system during different times since certain environmental systems may contribute more to determining the degree of differentiation of the quantum property that the system under analysis might end up with. For example, at least in the case of GRW, in the Stern-Gerlach apparatus, the (reversible decohering) interaction between the spin and the position degrees of freedom of the particle crucially contributes to measuring the degree of differentiation of spin-z, *but not* the stability of that quantum property and the determinacy that it arises. Afterward, the degrees of freedom of the particles that constitute the screen detector can be regarded (let's assume that there is collapse at the

[33] Note that, if we had collapse, the quantum property of the non-generator system would be represented either by $|\uparrow_z>_{S^*}$ or $|\downarrow_z>_{S^*}$ plus the spin-z observable. The determinate values that arise from the spin-z quantum property are represented by $\uparrow_z$ or $\downarrow_z$.

screen) as contributing to the particle having a stably differentiated position, which ends up leading it to also have a stably differentiated spin. So, the degree of the stably differentiated spin that the particle ends up with depends on the interaction that started previously with the subsystem of the particle that has the quantum property position. I will make this idea more precise below by distinguishing different kinds of interactions. Nevertheless, depending on the context, note that both reversible and irreversible decoherence allow us to measure the degree of differentiation of a quantum property via the degree of entanglement/distinguishability of the quantum states of the environment that are correlated with the quantum states concerning that quantum property.

Finally, for some QTs, it's necessary to analyze whether decoherence involves generators that very likely will have generative quantum properties, giving rise to the target system having a quantum property stably differentiated to some degree. As we saw in the GRW case, this should be an environment that collapses the target system in such a way that *it distinguishes* its different quantum states that were previously in a superposition.

As mentioned before, differentiation and determinacy are related, and this allows for an analysis of quantum indeterminacy and determinacy. This relation will establish that a property P*, in this case, a value property, is the property of having some other property P** having specific features. So, I will consider that

For a system to have a value v of P (where P could be energy, position, etc.) with a non-minimal degree of determinacy D is to have stably differentiated quantum property D-P to a non-minimal degree D* where D=D*. A system with a quantum property (fully) stably differentiated will have a determinate value of P.*

On the other hand, indeterminacy and undifferentiation are related,

For a system to have an indeterminate value of P is to have an undifferentiated quantum property.

Note that according to this relation, we have *multiple* quantum properties concerning P, represented by quantum states and observables, that correspond to a nonmaximally determinate value of P.[34] Just think about the variety of eigenstates of an observable concerning P that we can superpose and/or entangle with the quantum states of other systems to get quantum states that allow us to represent an indeterminate value of P.

Now that I have presented the ontology of properties that GQT will adopt in this article, I will turn to two structural features, which will help to give rise to different quantum theories. Certain structures, which include different kinds of interactions, account for how determinacy arises or not. Importantly, *what constitutes an interaction* how to infer it, and the different interactions that belong to the structure of interactions, varies according to the QT. Kinds of interactions between systems with undifferentiated quantum properties form structural features called *Indetermination Structures (ISs)*, where these interactions don’t involve or give rise to any system having a determinate value. ISs are one of the structural features assumed by GQT.

In GRW, what I will call *collapse-ISs* are represented and inferred via equations such as (1). Systems that don’t belong to ISs belong to *Determination Structures* (DSs), which also involve different kinds of interactions between systems. I will call them *structural generators* since they give rise to determinacy. I will call the DSs for generative-GRW, collapse-DSs. DSs is the last feature considered by GQT that I will present in this article. As will become clearer, each QT may adopt different DSs, ISs, property ontologies, generators, stability conditions, generative properties, and kinds of determinate values that generators generate. Also, as can be seen, these seven features are related to each other.

DSs and ISs can have a structure that may sometimes be represented by directed graphs, undirected graphs, or a hybrid (thus, being structures). Nodes represent systems, and edges between nodes represent certain kinds of interactions. One of them is *Stable Differentiation Interactions* (*SDIs*), which involves an arrow that goes from the generator or generators to the target system, leading them to have determinate values.

On the other hand, we have *Unstable Differentiation Interactions (UDIs)*, which are a sub-kind of ISs. UDIs are interactions between systems S’ and S’’ in which *if* some generator S stably differentiated a quantum property of S’/S’’, it would also stably differentiate a quantum property of S’’/S’ to a degree inferred from how much the quantum states of S’/S’’ distinguish the quantum states of S’’/S’ (or in other words, how

[34] Note also that this relation doesn’t imply that undifferentiated quantum properties are more fundamental than indeterminate value properties.

much the quantum states of S'/S'' are distinguishable). For instance, in the Stern-Gerlach case above, if some environment E in the screen stably differentiates the position quantum property of system S'' (which is a subsystem of the particle S), the spin-z of S' (another subsystem of S) is stably differentiated to a degree D* that is quantified by the overlap of the quantum states in the position basis of S'' that are entangled with the states of S'. Also, we have UDIs where one or both systems are generators, and if a quantum property of S'/S'' became stably differentiated, a quantum property of S''/S' would also become stably differentiated, where such degree of differentiation would be measured like in the above case. As I will explain, UDIs might have a direction.

UDIs can be inferred via reversible decoherence with no collapse like the one we have seen above, or simply when we have entangled systems. So, as we can see, unstable differentiation interactions don't give rise to an irreversible qua stable process, but instead to a *reversible qua unstable process*. Therefore, they don't change the stable differentiation of quantum properties that systems have although they could end up leading to processes that change it as I have explained above.

I will now introduce other interactions between systems that belong to ISs with an example that shows how generative-GRW accounts for interference phenomena. I will also demonstrate some extra explanatory resources that GQT allows for in accounting for interference phenomena, although builders of generative quantum theories might not wish to assume them.[35]

I will consider that systems can occupy multiple "locations," allowing us to represent the relations of influence behind interference phenomena, but without appealing to the wavefunction. The trick is to use the interactions that DSs and ISs allow for. When systems have an indeterminate position value, they are associated with multiple locations, and we can call each system-location pair a "part" of the system, and these parts in these multiple locations interact via *potential destruction interactions*. So, the latter are self-interactions that systems develop between the different parts of themselves that occupy different regions of spacetime. These interactions also belong to collapse-ISs, being reversible.

Relatedly, collapse-DSs also involve self-interactions called (*actual) destruction interactions*, and they arise from the potential ones. This interaction arises when one part of the system has a quantum property stably differentiated, leading the system in the other

[35] They may wish to not introduce the interactions that I will introduce below and "systems having different locations." However, this will likely diminish their explanatory resources.

locations to not exist anymore (irreversibly). So, it occurs when a system goes from having an indeterminate position to a determinate one Note that when a potential destruction interaction turns into actual destruction interaction, we have the phenomenon typically called *collapse of the wavefunction* in ontologies that reify it. Let's see how this works by considering a system that goes through a Stern-Gerlach interferometer with a detector placed in one of the arms. Let's, for example, assume that we have a neutron S constituted by system S' having, among others, the quantum property position and system S* having, among others, the quantum property spin-x, which initially are stably differentiated when the electron is prepared. When it reaches the first beam splitter, the system is split into two locations, having an undifferentiated position and spin-z. So, between the two locations, it's indeterminate where S' is. Undirected potential destruction interactions are developed between the parts of the system at these locations. They are undirected interactions because they don't have any direction of influence. Also, S' and S^* develop a directed UDI, since S' could end up stably differentiating S^*, but not vice-versa. The particle's quantum state is the one of eq. (1).

When the system interacts with a detector placed in one arm of the interferometer, the energy of the particle is stably differentiated by this detector, where the quantum state just before collapse is

$$|\Psi(\mathrm{t}'')>=\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_{S^*}|up\rangle_{S'}|E_{detected\ D1}\rangle+ \\ |\downarrow_z\rangle_{S^*}|down\rangle_{S'}|E_{Not\ detected\ D1}\rangle). \tag{5}$$

So, just before the collapse, the detector has for very brief moments an indeterminate location of its pointer. Let's suppose that system S is stably differentiated by D1. S' in the other branch of the interferometer will "destroyed." We would obtain $|\Psi'>\approx|\uparrow_z>_{S^*}|up>_{S'}\ |E_{detected\ D1}>$, with S having determinate value $\uparrow_z$ and up, and the rest of the systems that constitute the detector having determinate values correlated with these ones.

Note that the structure of the destruction relations is not directly represented via the quantum state, but rather inferred from it and represented via the directed graphs (more on this below). Note also that although the state of the whole system after the collapse is not an eigenstate of position, this is unproblematic because of the nonliteralistic representational role quantum states have for GQT. The system being close to being in a quantum state associated with these properties is enough to represent them.

Let's now consider an EPR-Bell scenario,[36] where space-like separated Alice and Bob perform random measurement on systems in a singlet-state, giving rise to correlations. To account for EPR-Bell-like correlations, we can also use DSs and ISs. Consider the state below, representing particles S_A and S_B before either Alice or Bob measuring them,

$$|\Psi(\mathrm{t})>=\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_A|\downarrow_z\rangle_B + |\downarrow_z\rangle_A|\uparrow_z\rangle_B)\,|R\rangle_{E_A}\,|R'\rangle_{E_B}\,\,|R''\rangle_{L_A}|R''\rangle_{L_B}\,. \quad (5)$$

Above we have two systems, E_A and E_B, with position R and R', respectively, and two systems A and B, each with an undifferentiated spin in all directions. L_A and L_B are the measurement devices of Alice and Bob before interacting with their target systems. Taking into account the above entangled state, it is considered that the structure of the IS is composed by systems A and B connected by an undirected (non-local) UDI. It is undirected because it can go both ways when one of the systems' spin in a direction becomes stably differentiated.

Afterwards, it can happen (for example) that, in a certain reference frame, L_B and E_B interact first with B, and we obtain the following quantum state just before collapse,

$$|\Psi(\mathrm{t})>=\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_A|\downarrow_z\rangle_B|down'\rangle_{E_B}|down''\rangle_{L_B} + |\downarrow_z\rangle_A|\uparrow_z\rangle_B|up'\rangle_{E_B}|up''\rangle_{L_B}\,)\,|R\rangle_{E_A}\,\,|R'''\rangle_{L_A}\,. \quad (6)$$

L_B will very likely have a stably differentiated position and trigger a collapse process, which stably differentiates the quantum properties of $E_B, B,$ and A, and leads the potential destruction relations that arose to become destruction relations. Below (Figure 1), we can see a directed graph representing the structure of the DS that is formed.

[36] Bell (1964).

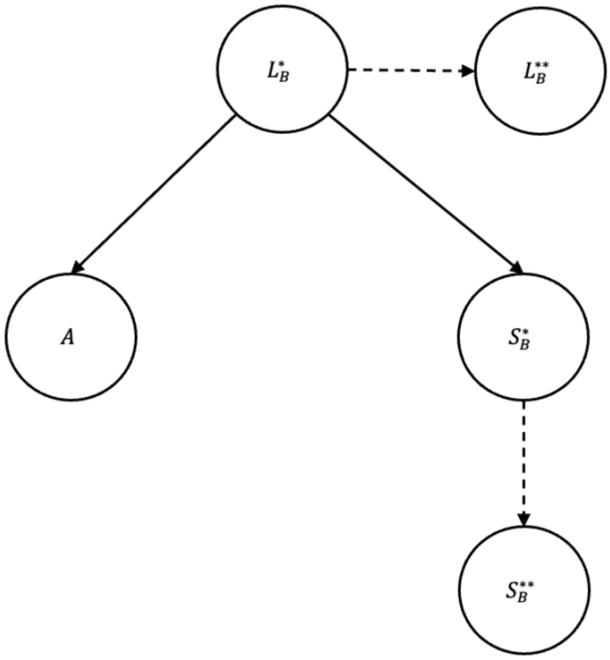

Figure 1 Directed graph representing a collapse-DS. Dashed arrows are destruction relations with a possible direction. The system arising in a determinate location (I have represented the part of the system at this location with a star) leads to the disappearance of the system being in the other location represented via a double star. The rest of the arrows are stable differentiation interactions.

To summarize, in this section, we have seen seven interrelated features postulated by GQT: a property ontology, generators, generative properties, the kinds of determinate values that generators generate, stability conditions, DSs, and ISs. As it will become clear, the combination of different sets of these features helps generate different quantum theories.

2.2. The generative-MWI and generative-single-world-relationalism

Let's turn to different versions of the generative-Many-World Interpretation (MWI), and single-world relationalist views. Unlike generative-GRW and, as we will see, generative-Bohmian mechanics, these views don't necessarily consider that particles play a fundamental role.

Like in generative-GRW, all systems have indeterminate values by default. Now, certain interactions give rise deterministically to multiple copies of systems each with the different possible stably differentiated quantum properties and determinate values, giving rise to what is typically called different worlds corresponding to different sets of determinate values. Each world is represented by each term in a certain superposition. Unlike generative-GRW, in principle, systems with diverse quantum properties are generators, not just systems with positions. So, many kinds of systems have the capacity to give rise to determinate values individually or at least collectively.

In this case, the process of branching into different worlds is the process of stable differentiation. The pattern explained in the previous section is repeated here: when generators have generative quantum properties, they can stably differentiate the quantum properties of the other systems and thus lead them to have determinate values. However, generative-MWI adopts stability conditions (section 2.1) where, in order for the target system to have a stably differentiated quantum property, it has to suffer a quasi-irreversible process due to its interactions with generators having a generative quantum property. This process is represented and inferred via the irreversible process of decoherence, where generators decohere the target system. Relatedly, like I have explained in the previous sections, decoherence is used to represent and infer which systems are generators, and the properties of generators that are generative and hence stably differentiated, giving rise to this process. On the other hand, like I also have explained in the previous section, via entanglement and reversible decoherence, we represent and infer those systems that have an undifferentiated quantum property in interactions with other systems, and thus, when systems don't have generative quantum properties.

I will present the different generative-MWI views via examples in which we have a Bell scenario where Alice (Lab A) and Bob (Lab B) can measure their systems in only two possible directions. I will start with a version of MWI where there is "local" branching,[37] calling it *generative-quasi-local-MWI*. For heuristic reasons, I will put a subscript DS in the quantum states of systems that are generators and will have a generative quantum property in the interactions under analysis, and thus give rise to interactions belonging to a DS, stably differentiating other systems' quantum properties. Furthermore, systems with different subscripts will belong to different *quasi-local-MWI-DSs*.

So, consider the following state,

[37] See Sebens & Carroll (2018) for the distinction between local and global branching.

$$|\Psi(t) >_{A+B} = \frac{1}{\sqrt{2}}(|\uparrow_z\rangle_A| \downarrow_z\rangle_B - |\downarrow_z\rangle_A| \uparrow_z\rangle_B) \, |E_{ready}\rangle_{Lab\ A\ DS'}|E'_{ready}\rangle_{Lab\ B\ DS''}. \tag{7}$$

Like in generative-GRW, we have UDIs involving A and B. When Bob interacts with his system, he stably differentiates the spin-z quantum property of system B, which also leads to the stable differentiation of the spin-z of A. Such determinate values result in two worlds, or more precisely, two new quasi-local-MWI-DSs,

$$|\Psi(t') >= \frac{1}{\sqrt{2}}\Big(|\uparrow_z\rangle_A| \downarrow_z\rangle_B|E'_{\downarrow_z}\rangle_{Lab\ B\ DS'} - |\downarrow_z\rangle_A| \uparrow_z\rangle_B|E'_{\uparrow_z}\rangle_{Lab\ B\ DS'}\Big) \, |E_{ready}\rangle_{Lab\ A\ DS''}. \tag{8}$$

Note that Bob doesn't affect the branching of Alice. Only when Alice interacts with A will she branch into two other worlds, obtaining two determinate values. Those values are only shared between the different versions of Alice and Bob if they meet.

Note that, before the above interaction, Lab B can have a stably differentiated quantum property (being represented by $|E'_{ready}\rangle_{Lab\ B\ DS''}$ plus the observable that this state is an eigenstate of) due to interactions that Lab B is developing with other systems not included in the model. So, systems that start having stably differentiated quantum properties may persist in having stably differentiated quantum properties through interactions, forming different worlds. The same in the case of Lab A.

As I have mentioned, GQT allows us to play around with the kinds of determinate values that are generated. Instead of giving rise to multiple determinate values deterministically, we could have a theory like the above one, but generators give rise indeterministically to single relative determinate values, which are relative to the different generator systems,[38] and A would not be connected with B via a UDI. So, the stable differentiation of properties of A would not affect the one of B, and vice-versa. Furthermore, for Alice (if they don't interact), Bob and his system would have indeterminate values, and vice-versa. This *generative-single-world-relationalism* resembles in some ways other relationalist theories, such as Relational Quantum Mechanics and Healey's pragmatism.[39]

[38] See also the beginning of the previous section.
[39] Rovelli (1996), Di Biagio & Rovelli (2021), and Healey (2017).

Furthermore, briefly, if we wanted a generative-single-world-relationalist theory that resembles more Relational Quantum Mechanics (RQM), we would consider that any system is a generator and gives rise to/generates relative determinate values upon *any* interaction. So, all quantum properties assumed by systems under interactions are generative. However, when not interacting, it is considered that systems have indeterminate values relative to each other. Then, we would consider that the role of decoherence is to infer when relative determinate values of a target system S and records of those values are inevitably shared between certain (environmental) larger systems S', S'', etc. that also interact, where S' locally interacts first with S, decohering it. Then S'' interacts with S', gets entangled with S and S', and obtains a record of the determinate value of S, and so on. In other words, decoherence is used to infer when certain systems inevitably stably differentiate the quantum properties of each other, giving rise to shared relative determinate values concerning the systems they interact with, or records of determinate values. The above chains of local interactions would be the DSs for *generative-RQM*.

GQT also allows us to play around with the structure of DSs and ISs and generate other generative-MWIs. For instance, in one generative-MWI we could have an IS where when Bob interacts with his system, he leads B to have a stably differentiated spin-z quantum property, *but this doesn't* lead A to have a stably differentiated spin-z, and vice-versa, and so we wouldn't have the above UDIs. This renders the MWI local in the sense that there is no influence between Alice and Bob in so far that they can be considered space-like separated.[40] Let's call this version, generative-local-MWI. Another generative-MWI would consider that instead of preexistent non-local UDIs, we have a theory with SDIs leading to non-local interactions between systems having different stably differentiated quantum properties over time. These SDIs would establish which systems belong to the same world. Let's call it *generative-global-MWI*. Bob and Alice would be connected via an SDI, and the splitting into branches of Bob when he measures his system would non-locally split Alice into multiple worlds even before she does her measurement or vice-versa. The resultant worlds of this branching would each contain different systems connected by SDIs that establish if they belong to the same world.

[40] There are issues here regarding how we can determine space-like separation if Alice and Bob don't share the same world. I will discuss a related issue in section 3.

2.3. The generative-Bohmian mechanics

Like generative-GRW, *generative-Bohmian mechanics* considers systems with quantum properties position as generators. The positions and velocities will be generative quantum properties,[41] being, by default, stably differentiated. The rest of the quantum properties will lead to a behavior similar to GRW, but without irreversibility since the theory is deterministic. Like in generative-GRW, we have fundamental particle quantum systems. The guiding equation represents the velocity of the particles with a stably differentiated position and how the latter changes over time, where this equation depends on the quantum states of systems.

The degree of decoherence or entanglement between the quantum states of the target system and the wavefunction of the particles in the position basis allows for a measure of the degree of stable differentiation of a quantum property of the target system upon interactions with these later systems. For instance, in the case of spin in a certain direction, the stable differentiation is measured via the overlap of the wavefunction in the position basis, where such wavefunctions distinguish the eigenstates of spin in that direction. The stable differentiation of other quantum properties, such as the energy of the particle, can be measured via the decoherence of the particle wavefunction by its environment constituted by systems that have the position quantum property.

To present generative-Bohmian mechanics in more detail, I will go over examples. Bohmian mechanics, being a hidden variable theory, leads also to the interpretation of quantum states as concerning our ignorance about which quantum properties of the particle are stably differentiated. Let's consider the one particle case in a certain Stern-Gerlach interferometer experiment. In the beginning, we have a particle constituted by two subsystems, one subsystem A with an undifferentiated spin-z and a subsystem E_A with a stably differentiated position in the region R ,

$$|\Psi(\mathrm{t}) >= \frac{1}{\sqrt{2}}(|\uparrow_z\rangle + |\downarrow_z\rangle)|R\rangle_{E_A} . \qquad (9)$$

The eigenstate of the position of E_A, $|R >_{E_A}$, concern our ignorance about the current value of the position of a particle. Like in collapse theories (non-mandatorily) I will proceed in a different way to account more satisfactorily for interference. This

[41] Why assume that these are the ones? We can point to, for example, to these being the only ones present in all interactions that give rise to determinate values, having an important explanatory role in the theory.

version of generative-Bohmian mechanics considers that it is associated to each particle a so-called *partner particle*. Partner particles are systems with the quantum property position and behave like those systems in GRW, having different "parts" in different spatiotemporal locations, but now we don't have irreversible destruction relations.

Partner particles will play the role of the branches of the wavefunction (including the empty branches, i.e., the branches that don't have particles) and account for interference without reifying the wavefunction, although they are inferred via it. Instead of having a particle "carried by a wave," we rather have a particle interacting with its partner particle. Like other quantum properties in generative-Bohmian mechanics, the position of a partner particle can be undifferentiated or stably differentiated to a degree where the degree of differentiation is measured via the amount of irreversible decoherence that the wavefunction associated with the particle and the partner particle suffers caused by the interaction with an environment. Also, when the wavefunction of the partner particle is in an eigenstate of the position operator, it has a determinate value of position, which will coincide with the one of its associated particle.

Let's then continue with our Stern-Gerlach interferometer example. Let's consider a system that passes by a Stern-Gerlach device, giving rise to a particle in the arms of the interferometer that has a stably differentiated position and spin-z as subsystems, and a partner particle with an undifferentiated position (no irreversible decoherence is involved). We are ignorant about the determinate value of the spin-z of the particle because we are ignorant about the initial conditions/position of the particle that entered the interferometer. Like in collapse theories, the two locations of the parts of the partner particle are interacting via potential destruction interactions when its position is indeterminate. We represent the state of this particle and its partner particle via

$$|\Psi(\mathrm{t}')>=\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_B|up\rangle_{E_B\,DS}+|\downarrow_z\rangle_B|down\rangle_{E_B\,DS}). \quad (10)$$

This interaction turns into a destruction interaction when one of the parts of the partner particle has a stably differentiated position due to, for example, a larger system such as a measurement device. However, contrary to collapse theories, the destruction interaction can be reversed (after a long time quantified by the decoherence timescale) to a potential one.

If the interferometer is set in the appropriate way, the particle and its partner can give rise to interference.[42] The degree of differentiation of the rest of the quantum properties (beyond position and spin) depends on how differentiated they are by systems with the quantum property position. If in the above situation, we measure the system by placing a detector at one of the arms of the interferometer, the interaction between gives rise (for example) to the particle having a stably differentiated energy. Also, as I have said, it will stably differentiate the position of the partner particle (which will have a determinate position), and the other part of the partner particle that also goes through the other side will disappear. Thus, we can update the wavefunction of the systems to an (effective) wavefunction of the system, which represents the particle and its partner particle with determinate values.

Let's see what the SDIs and ISs are for two particles with a stably differentiated position, and undifferentiated spin in any direction. To do that, let's consider the again the EPR-Bell scenario with the quantum systems prepared at the source in the state of eq. (5), but let's ignore the measurement devices of Alice and Bob. We have two systems, E_A and E_B, with stably differentiated position, which together with systems A and B each with an undifferentiated spin in any direction, constitute two particles S_A and S_B, respectively.

The non-local structure of ISs is at least represented and inferred via the entangled states between systems and other equations of Bohmian mechanics. Subsystems of the particle with undifferentiated quantum properties form non-local UDIs like in generative-GRW and in the generative-quasi-local-MWI. Local interactions between the generators and A/B lead A/B to have a stably differentiated quantum property (e.g., spin in a certain direction) and lead to a non-local stable differentiation of a quantum property of B/A. This changes the position determinate value of E_B/E_A when it interacts with B/A. Let's suppose that a magnetic field acts on particle S_A in such a way that E_A interacts with A where this interaction ends up stably differentiating the spin-z of A, changing the determinate value of E_A. Then, this also leads to the non-local stable differentiation of the spin-z of B. Furthermore, when E_B and B interact, E_B will have a certain determinate value of position influenced by the determinate value of B. Updating the state to the one that resulted from the interactions, we end up, for example, with the following quantum state,

[42] Note that the stable differentiation of the spin quantum property here is more easily reversible.

$$|\Psi(t')>=|\uparrow_z\rangle_A|\downarrow_z\rangle_B|up\rangle_{E_A\,DS}\;|down\rangle_{E_B\,DS}. \tag{11}$$

If the ontology of generative-Bohmian mechanics seems unnatural to some readers, it is because Bohmian mechanics, due to its hidden variables, is unfriendly to indeterminacy.

2.4. The generative-EnDQT and generative-hybrid-classical-quantum-theories

In this section, I will show how GQT generates a QT that provides a way of moving beyond the MWI/GRW/Bohm orthodoxy altogether via Environmental Determinacy-based Quantum Theory (EnDQT).[43] It also allows us to formulate a local interpretation of QT in the domain where we know where to apply QT. As we will see, EnDQT is a local non-relationalist non-superdeterministic/non-retrocausal quantum theory that makes indeterminacy basic. Besides being local (more on what I mean by local below), another benefit of EnDQT is that it's a conservative view since it doesn't modify the fundamental equations of QT. I will also briefly go over hybrid classical-quantum theories, and explain some of their similarities with EnDQT.

Like the MWI and other relationalist views, for generative-EnDQT (henceforward, EnDQT) particles don't necessarily play a fundamental role. The stability conditions, i.e., the conditions under which a system comes to have a stably differentiated quantum property, can be understood via four conditions that form the core of EnDQT. Plus, EnDQT involves two hypotheses. The key innovation of EnDQT is the determination capacity (DC), which is the capacity that systems have to give rise to other systems having their quantum properties stably differentiated and to transmit the DC to other systems under interactions. As we will see, another innovation is the introduction of a new kind of generator.

We have then the following so-called conservative determination conditions (CDCs), which are called this way because they are the most conservative conditions for the DC to spread:

CDC1) The determination capacity (DC) of system X concerning system Y (DC-Y) is the capacity that X has while interacting with Y,

[43] Pipa (2023).

i) to allow Y to have a determinate value under this interaction with X that also leads X to have a determinate value, where X and Y have a determinate value in the same spacetime point.

ii) to provide the DC to Y concerning another system Z (DC-Z) if and only if a) Z starts interacting with Y while Y is already interacting with X, and b) Y has a determinate value due to X.

So, the DC propagates between systems via interactions because Z can then have the DC concerning a system K (DC-K), if and only a) K starts interacting with Z while Z is interacting with Y, and b) Z has a determinate value due to Y, and so on for a system L that interacts with K while K interacts with Z, etc. Note that X having a determinate value and Y having a determinate value in the interaction in i) is the same event (i.e., it occurs in the same spacetime point). This is why for EnDQT interactions give rise to determinate values.[44] So, the events involving the systems of the environment Y having a determinate value, when they lead to the target system having a determinate value, occur in the same spacetime point. This assumption is consistent with the assumption that for

[44] This is a conservative assumption since it agrees with how systems become entangled at a time in a local interaction. If system A gets entangled with system B, system B gets entangled with A. The quantum framework doesn't distinguish which one happens first. Also, if these systems had determinate values at the same time in different spatial regions, the related events would be space-like separated, and we would have relativistic reference frames where one event happens first, then the other, and thus we would fall into relationalism since which system has a determinate value would vary with the reference frame, unless we favored a preferred reference frame. Furthermore, if this was the case, it would be problematic to establish that the environment gave rise to the target systems having a determinate value. Now, why not consider instead that the events involving elementary systems of the environment having determinate values are time-like separated rather than occurring in the same spacetime point? This alternative assumption would be unsatisfactory since it could give rise to a certain future dependency in terms of when determinate values arise. To see this, let's assume that each system of the environment has the DC and interacts with the target system, having a determinate value in this interaction at different times (so, that these events are time-like separated), although the target system doesn't have yet a determinate value. Furthermore, let's consider that we have a process that doesn't give rise to decoherence because the environmental overlap terms oscillate between being zero and non-zero. So, the entanglement between the system and the target system would oscillate over time. Since the environment would have determinate values, due to their entanglement, this would allow for an observer to gain knowledge about the determinate value of the target system by looking at the environmental systems. Hence, we would have a contradiction with the assumption that the target system doesn't have a determinate value. To deal with this situation, one could argue that systems of the environment would only have determinate values in the present if there was decoherence due to these systems in the future. However, this would give rise to future dependency and likely either super determinism or retrocausality. Hence, I have considered that the target system and the environmental systems have a determinate in the same spacetime point while they interact.

EnDQT, elements of the environment give rise to a target system having a determinate value as a collective (more on this below).[45][46]

How do the DCs propagate more concretely? The DC propagates between systems via local interactions over spacetime, so interactions only involve systems that aren't spacelike separated, where following the standard way,

For a system X to interact with system Y from time t to t', the quantum states of X and Y must at least evolve from t to t' under the Hamiltonian of interaction representing the local interaction between X and Y.

The chains of interactions that propagate the DC are called Stable Determination Chains (SDCs), and they are the DSs of EnDQT. All systems that don't belong to SDCs belong to ISs. Furthermore, contrary to some other QTs, there aren't interactions at a distance between systems that compose the DSs or the ISs. Also, in agreement with GQT we have that

CDC2) Interactions between system X and a set of systems that form a larger system Y, which have the DC, lead system X to have a certain determinate value, which corresponds to a certain quantum property stably differentiated, where the distinguishability of the physical state of Y concerning the possible determinate values of X allows us to infer if X will have a determinate value among the possible ones and when that happens. Such distinguishability is inferred via the decoherence of X by Y, and where it's indeterministic the values that will arise among the possible ones.

[45] One may object to the assumption that decohering systems of the environment and the target system have determinate values in the same spacetime point by mentioning the collisional models of decoherence (Zeh, 2003; Schlosshauer, 2007 and references therein). In these models, one might be tempted to consider that the collisions that give rise to decoherence happen over time, and hence, the events that give rise to decoherence should be time-like separated. However, note that if the collisions involving many systems happened at the same time, there wouldn't exist a significant change in these models. Also, the fundamental theory of the world will likely be one of quantum fields, which doesn't use the variable position, and ultimately, these models are only effective. The assumption regarding systems having determinate values in the same spacetime point shouldn't be strange. In physics, we are used to reify features that arise due to interactions, such as the bonding energy of atoms. Note that it's plausible that the notion of points is an idealization, and we should consider instead spacetime regions. It might also seem strange that systems have values in the same spacetime points/regions, but note that in quantum field theory, the same spacetime point is associated with the values of different fields.

[46] MWI proponents can also make the above assumptions regarding when branching or determinate values occur in spacetime since for this QT position isn't a privileged observable, and it's a view that can clearly appeal to QFT (see previous footnotes).

Now, we can use CSC2) to spell out CSC1) in terms of decoherence (more on how to understand decoherence according to EnDQT below).

CDC1*) The DC-Y of X is the capacity that X has while interacting with Y,

i*) to decohere Y, which leads both systems to have a determinate value. Let's suppose that system S in eq. (1) is an instance of X, and system E is an instance Y. The possible values of X are represented by $\uparrow_z$ and $\downarrow_z$. The possible values of Y are represented by $E_\uparrow$ and $E_\downarrow$.

ii*) to provide the DC-Z to Y if and only if ii*-a) Z starts interacting with Y while Y is interacting with X and ii*-b) Y is decohered by X.

CDC3) I will consider that two kinds of systems constitute an SDC:

-Initiator systems or initiators, which are systems that have the DC concerning any system by default (i.e., they always have the DC-X for any system X), i.e., independently of their interactions with other systems. Because of this, initiators are the systems that start SDCs.

-Non-initiator systems are systems that don’t have the DC concerning a system by default but have it due to their interactions with other systems that have the DC.

So, for EnDQT, like in some other generative QTs, the world is fundamentally constituted by systems with indeterminate values/undifferentiated quantum properties, which include *initiators*. The latter have the DC concerning any system by default, not having to have their quantum properties stably differentiated in a previous interaction to stably differentiate the quantum properties of other systems and transmit the DC. On the other hand, non-initiators have to have certain quantum properties stably differentiated due to some previous interactions to have the DC (more on this below).

Since systems are typically composed of many systems, EnDQT also assumes that

CDC4) For a system S to have the DC concerning some system S’, its subsystems must have the DC concerning S’ or its subsystems.

Let's consider a simple and idealized example. I will soon make this example more concrete further below via a related example. I will assume that systems interact quickly compared with how quickly they intrinsically evolve, so that, once again, we can neglect the systems' intrinsic evolution. This example will involve systems S_0, S_1, and S_2, where S_0 is an initiator, in a toy mini universe where the SDC that will be formed has the following structure: $S_0 \rightarrow S_1 \rightarrow S_2$. The arrows represent the stable differentiation of a quantum property of S_1 by S_0, which allows S_1 to stably differentiate a quantum property of S_2, having the DC-S_2.

Let's assume that S_2 starts interacting with S_1 while S_1 is interacting with S_0 so that S_1 has the DC-S_2, and S_1 can end up transmitting the DC to S_2 concerning some other system that S_2 might end up interacting with. However, when S_1 and S_2 begin interacting, let's assume that we can neglect the evolution of the quantum states of S_1 while S_0 and S_1 interact, such that we can idealize that S_1 and S_2 start interacting only when the interaction between S_0 and S_1 ends.[47] Thus, we can just analyze the evolution of the quantum states of S_0 while S_0 and S_1 are interacting, where this interaction ends approximately at t', and these systems have a determinate value at t'.

Let's then put a subscript SDC on the quantum states of a system if that system is an initiator or has the DC relative to some system belonging to an SDC. We then have the following interaction between S_0 and S_1,

$$\begin{gathered}|E_{ready}\rangle_{S_0\,SDC}\,(\alpha'|E_0'\rangle_{S_1}+\beta'|E_1'\rangle_{S_1})\ \rightarrow_{t'}\\ |E_0(t')\rangle_{S_0\,SDC}\ |E_0'\rangle_{S_1}+|E_1(t')\rangle_{S_0\,SDC}\ |E_1'\rangle_{S_1}.\end{gathered} \tag{12}$$

So, if $\langle E_0(t')|E_1(t')\rangle_{S_0\,SDC} \approx 0$ and $\langle E_1(t')|E_0(t')\rangle_{S_0\,SDC} \approx 0$ quasi-irreversibly when S_0 and S_1 end their interaction, S_1 will have a quantum property stably differentiated by S_0 and a determinate value of the associated quantum property (let's suppose that is either 0 or 1) that arises from its interaction with S_0, and acquires the DC-S_2 (given our idealization). I am assuming that occurs at t'. Let's further assume that S_1 has a determinate value 0. Then, the stably differentiated quantum property will be represented by $|E_0'\rangle_{S_1}$ and the observable that $|E_0'\rangle_{S_1}$ is an eigenstate of. Now, let's consider the

[47] We could similarly consider that while S_0 interacts with S_1, S_2 starts interacting with S_1 in such a way that it doesn't drive the states of S_1 out of being states that S_0 decoheres in the following sense: the Hamiltonian of interaction of S_0 and S_1 would still at least approximately commute with the (pointer) observable that these states are eigenstates of.

interaction between S_1 and S_2, which (assuming our idealization) starts when the interaction between S_0 and S_1 ends. Let's assume that it ends at t'',[48]

$$
\begin{gathered}
|E_0'\rangle_{S_1\,SDC}\big(\alpha|\uparrow\rangle_{S_2} + \beta|\downarrow\rangle_{S_2}\big) \rightarrow_{t''} \\
|E_0'^{\uparrow}(t'')\rangle_{S_1\,SDC}|\uparrow\rangle_{S_2} + |E_0'^{\downarrow}(t'')\rangle_{S_1\,SDC}|\downarrow\rangle_{S_2}.
\end{gathered}
\tag{13}
$$

The evolution of the interaction between S_1 and S_2 could be analyzed via the reduced density operator $\rho_{S_2}(t)$. This interaction will lead to the stable differentiation of a quantum property of S_2 and allow it to have a determinate value (↑ or ↓) if $\langle E_0'^{\uparrow}(t)|E_0'^{\downarrow}(t)\rangle_{S_1} \approx 0$ and $\langle E_0'^{\downarrow}(t)|E_0'^{\uparrow}(t)\rangle_{S_1} \approx 0$ quasi-irreversibly when S_1 and S_2 end their interaction. Let's assume that this interaction ends at t'', and these systems will have a determinate value at t''. So, S_1 will have another stably differentiated quantum property and a determinate value at t'' that arises from its interaction with S_2, where the possible values that it can have are represented via the eigenvalues of the observable that $|E_0'^{\uparrow}(t'')\rangle_B$ and $|E_0'^{\downarrow}(t'')\rangle_B$ are eigenstates of. Furthermore, S_2 could have the DC concerning some other system S_3 if it interacted with it before its interaction with S_2 ends. Note that since system S_0 is an initiator, it only has a determinate value during interactions associated with $|E_0(t')\rangle_{S_0\,SDC}$ or $|E_1(t')\rangle_{S_0\,SDC}$ and has the DC concerning any system.

So, for EnDQT irreversible decoherence is viewed as an inferential tool that represents how the systems that are part of the nodes of SDCs interact, and like generative-MWI and generative-Bohmian mechanics, to infer the time it takes for stable differentiation to occur. However, it's important to emphasize that now it is required that the systems that belong to the environment have the DC, in order for determinate values to arise. So, when there are interactions, but the systems involved don't belong to an SDC, not having the DC, their relevant quantum properties will remain undifferentiated. Thus, no determinate value arises, and we don't update the quantum state to the new state.

Let's now turn to the two hypotheses assumed by EnDQT, starting with the one regarding decoherence. EnDQT has a subtler view of decoherence than other QTs. Let's call the models of decoherence that represent the interactions between systems having the DC, starting with the initiators, *fundamental decoherence models*. These models don't involve extra considerations, such as if the environment is inaccessible or open. The

[48] Note that the quantum states of S_1 and S_2 absorbed their quantum amplitudes.

systems in CDC1-CDC4), and in the example above are represented via these models. On the other hand, the so-called *pragmatic decoherence models* don't necessarily track the interactions with systems that have the DC.

These models come in two kinds. We have seen them in the previous sections, but I will distinguish them here again to precisify some of their aspects and distinguish them from other processes. *Irreversible pragmatic decoherence models* are models that represent situations where it's considered that is impossible to reverse the process represented by them because they involve many systems, and where these situations may involve an environment that is open. These are the models typically associated with decoherence. We also have what I will call *reversible pragmatic decoherence models*. These are models that represent a process that apparently involves decoherence in the sense that it is modeled by the overlap terms of the environment going quasi-irreversibly to zero. However, someone in some privileged position could reverse this process via operations on the systems or (to put it less pragmatically) they don't involve enough degrees of freedom to be considered irreversible. So, these models aren't what we associate with decoherence.

Given the distinctions above, EnDQT also postulates the following hypothesis regarding the structure of the SDCs:

the SDCs in our world are widespread in such a way that irreversible pragmatic decoherence models in open environments track the interactions between systems that belong to SDCs, but there can also exist processes represented via reversible decoherence pragmatic models, where the latter are tracking the interactions between systems that don't belong to SDCs (SDCs-decoherence hypothesis).

So, via this hypothesis, EnDQT grounds the success of these pragmatic decoherence models in representing processes that give rise to determinate values. It's important to notice that depending on one's ingenuity, *in principle*, it's possible to isolate macroscopic systems from the influence of SDCs, and so for EnDQT, in principle, arbitrary systems can be in a superposition for an arbitrary amount of time. Thus, if this isolation is done properly in such a way that we can unitarily manipulate the contents of that region, we might have a process of reversible decoherence inside that region instead of an irreversible one. So, given the above hypothesis, if some situation, even involving interactions between macroscopic systems, is appropriately modeled by reversible pragmatic decoherence models, we can infer that we have managed to isolate the systems from the influence of SDCs. Of course, also given this hypothesis, in principle, doesn't mean in practice because our pragmatic models of decoherence tell us that it's very difficult to place large macroscopic systems in a superposition.

This view of EnDQT is contrary to what is often assumed by MWI-like views, which would consider that determinacy arises within a large enough isolated spatiotemporal region with systems decohering each other inside of it. The DC doesn't exist and matter. Note again that, contrary to most of the previous quantum theories, for EnDQT there aren't any non-local ISs or DSs connecting systems. Those structures arise and are maintained locally via their interactions. SDCs for EnDQT can be represented by directed graphs like the one in the example above, where the arrows represent the stable differentiation interactions arising between systems.

Now, we are in a better position to clarify how EnDQT relates to some of the other features of GQT. Contrary to the other QTs explained here (more on this in the next section), EnDQT has the benefit of explaining in a unificatory and parsimonious way via the initiators and the laws that describe/govern the interactions of systems that belong to the SDCs they give rise to, which systems can be generators and the generative quantum properties that they have. More concretely, initiators are a special kind of generators that have the capacity of allowing other systems to become generators when they interact with them. The generative quantum properties of generators are the properties that they have when they interact with other systems, giving rise to the latter having determinate values. Above, $|E_0(t')\rangle_{S_0\,SDC}$ or $|E_1(t')\rangle_{S_0\,SDC}$ and the respective observable that these quantum states are eigenstates of, represent those generative quantum properties. Systems that they interact with will be able to have determinate values and certain generative quantum properties, becoming generators. The possible generative quantum properties of S_1 are represented by $|E_0'^{\uparrow}(t'')\rangle_{S_1}$ or $|E_0'^{\downarrow}(t'')\rangle_{S_1}$, and the observable that these quantum states are eigenstates of, which gives rise to S_2 having a determinate value. So, we can trace the capacity of systems having generative quantum properties and being generators to interactions that ultimately originated with initiators.

The second hypothesis aims to address the question regarding what kind of systems initiators are. The inflaton is one possible candidate for an initiator because of its privileged and influential role in the history of the universe, which accounts for our belief that systems with determinate values are widespread (i.e., classicality is widespread).[49] So, the inflaton field with its quantum properties occupying regions of spacetime would be the initiator.

To clarify, notice that ultimately, the description of the inflaton field and the rest of the fields interacting with it would need to be quantum field theoretic. I haven't shown how GQT can be understood in the context of quantum field theory, but in principle, such an extension won't be problematic. Briefly, in one possible approach, we make a distinction between a *quantum field system*, which occupies multiple spacetime regions and quantum systems, which concern local spacetime regions. A quantum system is one or more quantum field systems in a spacetime region. More concretely, to obtain a quantum system, we associate to a quantum field system in a spacetime region, such as the inflaton field in the spatial region x at t (whose observable is $\hat{\phi}(x,t)$), collections of quantum properties represented by the wavefunctional $\Psi[\phi,t]$.[50] The latter assigns a complex amplitude to each possible configuration of classical fields in that spacetime region, yielding a superposition of these configurations. The quantum properties of the quantum system (which concerns that region) will also be represented by the observables that act on the wavefunctional in that region. So, although a quantum field system is associated with multiple spacetime regions, the DC is transmitted between quantum systems occupying local regions and via local interactions since the observables (including the field observables such as $\hat{\phi}(x,t)$)[51] representing quantum systems and quantum properties concern local spacetime regions. Thus, it's expected that quantum systems will have stably differentiated quantum properties and spread the DC in local regions of spacetime. The inflaton field is the initiator, but it transmits the DC via local interactions.[52]

One of the reasons to consider the inflaton field (and the quantum systems that arise from this field) as a plausible candidate for an initiator is that it allows us to explain why we can sometimes maintain the coherence of quantum systems in quasi-isolated spatiotemporal regions. If there were initiators that could start SDCs in any region, it would be very difficult or impossible to maintain such coherence because they would

[49] See Pipa (2023).
[50] The wave functional maps functions to numbers. See, e.g., Kuhlmann (2018) for an introduction to quantum fields.
[51] Via the so-called microcausality conditions.
[52] This approach has some issues (see, e.g., Sebens, 2022). Lagrangian approaches, Fock spaces, and other approaches may help complement it in making inferences and representing quantum properties. GQT doesn't need to rely on one single mathematical framework.

destroy superpositions. We can allow for initiators that only manifested themselves at the beginning of the universe by observing that it's standardly considered that, at least in our universe, the inflaton field reached the absolute minimum of its potential and has been staying there.[53] Then, for example, if we consider the condition that this minimum corresponds to the point where the field is zero and if we consider that the coupling of the inflaton field to all other fields in the Lagrangian density that describes/governs our universe depends on the value of the inflaton field in such a way that the interaction terms representing these interactions are zero when the field zero, we can consider that the inflaton field in the stages of the evolution of the universe after the reheating phase will at least rarely interact with other fields/systems.[54] So, it will (at least) rarely give rise to SDCs after the reheating phase, which is our current phase. Let's represent the Lagrangian of our universe obeying these conditions as $\mathcal{L}_{SDC}$. So, the second hypothesis is that

at least most current SDCs started in the early universe, and initiators had a privileged role in this stage, giving rise to these SDCs, and where the initiators are the inflaton field described via $\mathcal{L}_{\mathrm{SDC}}$ (inflationary-starting hypothesis).

This is one possible concrete hypothesis for what initiators are, being an instance of the more abstract *SDCs-starting hypothesis*, which establishes when SDCs started.[55] I regard this latter hypothesis is a placeholder for current and future cosmology. Given the current evidence for inflation, this is the initiator adopted. As I have argued (Pipa, 2023), the specialness of initiators is, in principle, unproblematic because our evidence points towards early universe events involving some special physical phenomena and can provide other scientific and philosophical advantages (more on this in the next section).

To get a better sense of how EnDQT works, now, we can go back to the above toy model and extend it to make it more concrete via another toy model but keeping its simplifying assumptions regarding the interactions between systems. In this toy model, we consider that now we have an initiator S_0 constituted by sets of harmonic oscillators, i.e., a reservoir of bosonic field modes. Each set of systems interacts with one two-level/spin-1/2 system that is a subsystem of a larger system S'_1. These interactions would

[53] See, e.g., Liddle & Lyth (2009).
[54] See, e.g., Kiefer & Polarski (2009) for models of decoherence involving the decoherence of the inflaton field, and a discussion of the various possible kinds of environmental systems. See Pipa (2023) for more references concerning decoherence models of the inflaton field.
[55] Pipa (2023).

be represented by a well-known spin-boson decoherence model.[56] The subsystems of S_0 would effectively represent a collection of modes of the inflaton field that interact with other systems in regions of spacetime, and they would be the "environment" for each spin-1/2 subsystem of S'_1. For simplicity, we consider a Hamiltonian that doesn't contain the so-called tunneling term and start with the environment in the ground state. The initial state of the subsystems of S_0 being in the ground state would approximate the Bunch-Davies vacuum[57] and allow us to solve this spin-boson decoherence model without appealing to master equations. The Bunch-Davies vacuum is the local quantum vacuum state for a homogeneous, isotropic, inflationary spacetime, and it is considered to be the initial state of the fluctuations of the inflaton field.[58] So, I will consider that the elements of each set s_0^i of subsystems of S_0 would interact with one of the spin-1/2 subsystems of S'_1, and the number of subsystems that constitute each set s'^i_0 would be much bigger than one, in such a way that each decohere one of the subsystems of S_1. The possible values of each elementary subsystem of S'_1 let's assume that would be $+1/2$ and $-1/2$ spin-z values.[59]

Now, instead of S_2, we would have a larger system S'_2, constituted by spin-1/2 subsystems. Each spin-1/2 subsystem of S'_2 interacts with members of the set s'^i_1 of subsystems of S_1, also constituted by spin-1/2 systems as we have seen. The number of elements of each s_1^i would be much higher than one in such a way that they decohere each subsystem of S'_2. This interaction would be modeled by the classic spin-spin model,[60] neglecting the Hamiltonian of interaction of the systems because we would consider that the interactions between systems are very quick compared with how these systems intrinsically evolve. This also would allow this model to be solved analytically. Each subsystem of S'_2 would serve as a target system system for an environment constituted by the systems that belong to s'^i_1. The possible values of each elementary subsystem of S'_2 let's assume that would be $+1/2$ and $-1/2$ spin-x values. This pattern could be repeated for each subsystem of system S_3 that interacts with a set of subsystems of S'_2, and so on for systems S_4,…, S_n.[61] It will lead to the formation of an SDC with n systems

[56] Leggett et al. (1987). See section 5.3.1 in Schlosshauer (2007) for an introduction.
[57] Bunch et al. (1997).
[58] More concretely, it is the minimum energy eigenstate of the Hamiltonian for the primordial fluctuations infinitely back in the past.
[59] Given the appropriate well-known Hamiltonian, see references above.
[60] Cucchietti et al. (2005) and Zurek (1982).
[61] Given again the appropriate well-known Hamiltonian, see references above.

and its subsystems. In this toy model, we could keep using the spin-spin decoherence models or other models.

An important benefit of EnDQT is that it provides a local common cause explanation of quantum correlations in the sense of not violating relativistic causality, i.e., without forcing us to assume that the causes of the events involved in those correlations aren't in their past lightcone and without invoking superdeterministic or retrocausal explanations (Figure 3). Let's see how SDCs and ISs help provide that explanation. First of all, note that EnDQT doesn't modify the fundamental equations of QT, and so, in principle, it can be rendered Lorentz-invariant, and thus, it can be compatible with relativity in this sense.[62] However, future work will provide a model of EnDQT where this is shown explicitly. Second, let's see how it deals with the EPR-Bell scenarios and Bell's theorem.

A widely accepted version of Bell's theorem involves, together with the no-superdeterminism assumption,[63] the factorizability condition,

$$P(AB|XY\Lambda) = P(A|X\Lambda)P(B|Y\Lambda). \quad (14)$$

The variables A, B, $\mathbf{\Lambda}$, X, and Y concern events embedded in a Minkowski spacetime. A and B represent the different measurement results of Alice and Bob, X and Y are the different possible choices of measurement settings for Alice and Bob. $\mathbf{\Lambda}$ represents some set of (classical) "hidden" variables in the past lightcone of A and B (see also Figure 3), representing the common causes of the correlations between X and Y. This condition is seen as a consequence of two assumptions:[64] the causes of an event are in its past lightcone, and the classical Reichenbach Common Cause Principle (CRCCP).

Briefly, the CRCCP states that if events A and B are correlated, then either A causes B, or B causes A, or both A and B have common causes $\mathbf{\Lambda}$, where conditioning on $\mathbf{\Lambda}$, A and B are decorrelated, i.e., $P(A, B|\,\boldsymbol{\Lambda}) = P(A|\,\boldsymbol{\Lambda})P(B|\,\boldsymbol{\Lambda})$. However, it's unclear whether we should accept that the probabilistic relations and conditions given by the CRCCP should, in general, represent a causal structure involving quantum systems, given their quantum indeterminate values, and how they evolve. The CRCCP can be seen as a

[62] Within the domain where we know where to apply QT.
[63] This assumption states that any events on a space-like hypersurface are uncorrelated with any set of interventions subsequent to it.
[64] Bell (1976, 1995, 2004). See also, e.g., Myrvold et al. (2021) and references therein.

consequence of the Classical Markov Condition (CMC), assumed by classical causal models (CCMs).[65]

The CMC connects the causal structure provided by some theory represented by a DAG with probabilistic statements. The CMC is the following,

let's assume we have a DAG G, representing a causal structure over the variables $\boldsymbol{V} = \{X_1, \dots, X_n\}$. A joint probability distribution $P(X_1, \dots, X_n)$ is *classical Markov* with respect to G if and only if it satisfies the following condition: for all distinct variables in $\boldsymbol{V}, P$ over these variables factorizes as $P(X_1, \dots, X_n) = \prod_j P\left(X_j \middle| Pa(X_j)\right)$, where $Pa(X_j)$ are the "parent nodes" of X_j, i.e., the nodes whose arrows from these nodes point to X_j.

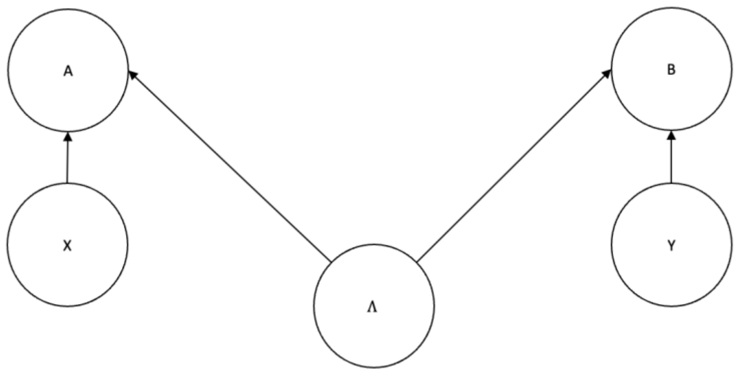

Figure 3: DAG of the common cause structure of Bell correlations, which respects relativity. This causal structure respects relativistic causality because X or A doesn't influence Y or B, and vice-versa, where these events may be spacelike separated. Moreover, no other variables influence the variables A, B, X, or Y, or they don't influence anything else. So, there are no retrocausal or superdeterministic causal relations.

The CMC for the DAG in Fig. 3, which respects relativity, allows us to derive the following equation (I will denote certain regions of spacetime, the related nodes, and variables whose values may be instantiated in those regions using the same letters),

$$P(AB|XY) = \sum_\Lambda P(\Lambda)\mathrm{P}(\mathrm{A}|\mathrm{X}\Lambda)\mathrm{P}(\mathrm{B}|\mathrm{Y}\Lambda). \quad (15)$$

[65] I will not derive it here, but see Hitchcock & Rédei (2021).

The acceptability of the CRCCP can be supported by the empirical success of the application of the CMC via CCMs (e.g., Pearl, 2009). EnDQT responds to Bell's theorem by rejecting that the CMC can be applied in general to accurately represent causal relations between quantum systems, understood here as relations of influence. Hence, it rejects the applicability of the CRCCP and the factorizability condition to make such accurate representation.

In Pipa (2023), I have provided various reasons why EnDQT rejects that the CMC accurately represents causal relations between quantum systems. The rough idea is that the use of the CMC is unjustified to make inferences about indeterministic causal relations between quantum systems having indeterminate values. Here, I will just briefly sketch how EnDQT uses a generalization of the CMC, the quantum Markov condition (QMC), and Quantum Causal Models (QCMs)[66] that adopt a quantum version of the CMC, to provide a local common cause explanation of Bell correlations.

Let's then do that.[67] Now, A, B, and Λ represent spacetime regions instead of classical variables. Consider below how, via the quantum Markov condition and a version of the Born rule, we can give a causal explanation of Bell correlations (Figure 4),

$$P(x,y|s,t) = Tr_{\Lambda AB}\left(\rho_{\Lambda}\rho_{A|\Lambda}\rho_{B|\Lambda}\tau_A^{x|s\,SDC} \otimes \tau_B^{y|t\,SDC}\right). \quad (16)$$

The systems that are prepared at the source are acting as common causes for Bell correlations. They have indeterminate values, until reaching the measurement devices of Alice and Bob, which gives rise to the correlated outcomes. The entangled state ρ_{Λ}, through its subsystems, represents these systems that are prepared at a source, which, for instance, can be systems having indeterminate values of spin-p, where p is ranging over all possible directions of spin. ρ_{Λ} and the quantum channels $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$ are used to separately represent each system prepared at source that travels to the different regions, and this is done by keeping track of the labels A and B.[68] So, each one of the systems evolves locally to region A/B, where Alice/Bob will influence the outcomes arising in those regions. When it comes to A, this influence is represented via the quantum channel $\rho_{A|\Lambda}$, and when it comes B, by $\rho_{B|\Lambda}$. More concretely, $\rho_{B|\Lambda}$ and $\rho_{A|\Lambda}$ are identity channels

[66] Costa & Shrapnel (2016), Allen et al. (2017), Barrett et al. (2019).
[67] Note that QCMs were so far developed only for the finite-dimensional Hilbert space, but in principle, this is not a fundamental limitation.
[68] See Nielsen & Chuang (2011).

that via their action on the density operator ρ_{Λ} , also represent the systems in region $\mathbf{\Lambda}$ that evolve to regions A and B, respectively. The influence that gives rise to the outcomes is also represented via the POVMs $\tau_A^{x|s\ SDC}$ in Alice's case, where s is her random measurement choice, and x is her outcome, and via $\tau_B^{y|t\ SDC}$ in Bob's case. The superscript SDC placed in the POVMs means that these are interventions/interactions that give rise to a determinate value, involving systems that are part of a local SDC, making others also part of an SDC. These interactions are represented by other types of edges in the DAG in Figure 2. In this case, Alice and Bob, due to their measurements, will lead the target systems to being part of an SDC because they also belong to SDCs, for example, giving rise to the systems having a determinate value of spin in a specific direction. So, via the above account, EnDQT uses QCMs to give a local common cause explanation of quantum correlations. It's important to notice that, by assuming GQT's perspective on quantum states, which doesn't reify them, we shouldn't consider that the measurement of Alice's on her system influences Bob's system, and vice-versa.

This scenario can be represented using a DAG, which I will call *EnDQT-causal-DAG*. The diagram shows the evolution of systems that are not part of an SDC but rather an IS, in grey. The evolution and interactions of systems that belong to an SDC are in black:[69]

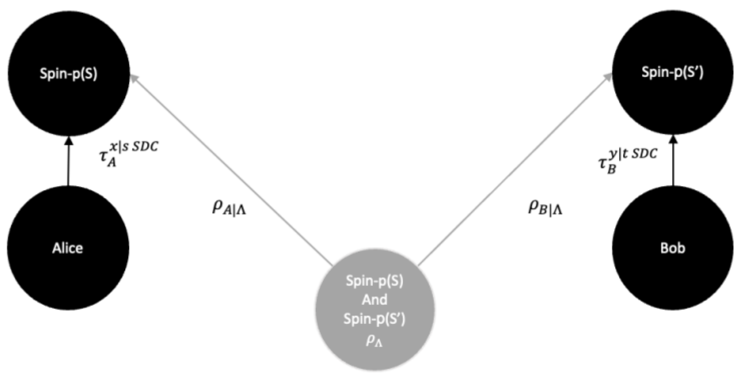

Figure 4: *EnDQT-causal-DAG* proposed by EnDQT, which allows for a non-relational local common cause explanation of Bell correlations.[70]

We see above the role of structural generators in giving a local common cause explanation of Bell correlations.

[69] See Pipa (2023) to see how EnDQT can account for interference locally via second quantization.
[70] Figure taken from Pipa (2023).

Another generative quantum theory leads to a version of hybrid classical quantum theories,[71] which I will call generative-hybrid. Due to reasons of space, here I will go over it briefly. In the case of this theory, we have a gravity-causes collapse theory, where there are classical systems that evolve fundamentally stochastically,[72] and quantum systems. The evolution of both is described/governed by a hybrid classical-quantum dynamics. Quantum systems, by default, belong to an IS and have undifferentiated quantum properties like EnDQT, and like EnDQT, there aren't any non-local ISs. Furthermore, classical systems are a collection of quantum properties that are always stably differentiated, e.g., the metric and its conjugate in the hybrid theory that aims to describe gravity, and occupy spatiotemporal regions.[73] Note that the metric as a field will have values throughout all spacetime, and like in the case of quantum systems when we have quantum field systems (see above), classical systems will pertain to certain spacetime regions.

The stochastic behavior of the metric is represented via a positive density operator. A classical-quantum state is the tensor product between these operators and quantum states/density operators. A classical-quantum system is a collection of the quantum properties of both, concerning certain regions of spacetime. Classical systems are generators and stably differentiate the quantum properties of quantum systems, and the latter also backreacts on the classical systems, affecting their evolution. DSs concern the local evolution of these classical systems and their interactions with quantum ones. Generative-hybrid is local and can also provide a local causal explanation of Bell correlations like EnDQT (more on this below),[74] but gravity is the sole responsible for determinate values arising.

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[71] See Oppenheim (2023) and, e.g., Diósi (1995).
[72] So that the gravitational field doesn't "reveal" the location of the quantum systems in its interactions with them, *collapsing* their quantum states, in certain situations in agreement with experiments. However, the greater the rate of *decoherence* induced by classical systems on quantum systems the lower the amount of diffusion/stochasticity induced by the quantum systems on the metric and their conjugate momenta of the classical system (Oppenheim et al., 2023).
[73] I don't regard calling these properties quantum or not as a substantive issue in a fundamental theory. Like in GRW, a quantum property doesn't need to be represented via standard QT.
[74] This is why hybrid classical-quantum theories shouldn't reify the quantum state because this doesn't lead to inferences about non-local causal relations, adopting GQT point of view.

3. Generative Quantum Theory vs Wavefunction Realism and Primitive Ontology

Let's now compare GQT with Wavefunction Realism (WR) and Primitive Ontology (PO). I will argue that GQT has certain important benefits that these frameworks don't offer, and without some of their notorious costs.

First, GQT offers a better way of making sense of the nature of the wavefunction or quantum state or density operators or matrices than WR and PO (I will refer to density operators also as quantum states from now on).[75] WR is an ontology that considers that the fundamental entity represented by QT is a wavefunction living in a 3N configuration space where N is the number of existing particles.[76] As it's well-known, the main challenge of WR is to give a plausible account of how to derive and make sense of the spatial three-dimensional manifest image from this more fundamental space. This is problematic, given the evidence that we have that, at least in the classical regime, systems occupy regions of spacetime.

This brings me to the PO. According to this view, what is fundamental are entities with determinate locations in spacetime, having determinate features, like flashes, mass densities, etc., also known as local beables. This contrasts with the GQT since, in the latter case, fundamental entities can have indeterminate locations. Another feature of the PO framework is their view of the wavefunction/quantum states, which are to be considered fundamental, but it's typically considered not to represent matter. It typically rather has a nomological character, governing or describing the behavior of the PO/local *beables*. Although PO advocates may also allow the wavefunction to be a physical wave in a high-dimensional space, I will specialize my discussion on the former case since it sets it more apart from GQT and WR. PO endorses a revisionist attitude towards the laws of nature by considering that a complicated object such as a wavefunction/quantum state, which is also allowed to change over time, is a law.[77]

[75] I am also assuming that PO proponents can assume that density operators have a nomological character.

[76] The wavefunction that represents this field mathematically concerns quantum states expressed in a basis. Disregarding the spin, in non-relativistic QT, the wavefunction is typically considered a *square-integrable* and smooth function whose domain is the $\mathbb{R}^{3N}$ configuration space where N is the number of particles, and the range is complex numbers.

[77] One strategy tries to address this worry by arguing that the fundamental wavefunction of the universe behaves more like a law and may be simpler because it doesn't change over time (Goldstein & Zanghì, 2013). This is supported by the Wheeler-DeWitt equation assumed by some theories of quantum gravity. However, this strategy is highly speculative because it relies on an assumption that not all quantum gravity programs make.

GQT doesn't suffer from the issues associated with considering the wavefunction as an entity in a 3N dimensional space or a law. The quantum state is more like a distribution over a set of possibilities, and possibilities, unlike laws, change over time. Furthermore, although systems can have certain indeterminate locations, they can still occupy regions of spacetime. Thus, GQT offers a better way of making sense of the nature of quantum states or the wavefunction than WR and PO.

Second, contrary to these other frameworks, GQT is built in such a way that helps formulate new QTs, which may lead to scientific and philosophical progress (more on this in the next section). For example, GQT, in principle, can help generate new quantum theories (and associated ontologies) that adopt a strategy compatible with relativistic causality. Given the importance of relativistic causality, this should be regarded as a benefit. As I will argue, PO and WR lack this benefit.

We have seen EnDQT and a local version of the MWI above as examples of theories that GQT helped generate. Furthermore, by changing some of the features that EnDQT adopts, GQT can, in principle, help generate theories that are a hybrid of EnDQT and other quantum theories. As I will argue, these hybrids can or may lead to other theories that allow for the compatibility between QT and relativistic causality, plus have some other benefits. I will sketch three examples of these theories here and leave their development for future work.

Regarding what I will call *EnDQT-collapse*, we will adopt a different kind of generators and, more specifically, initiators. Systems with a specific quantum property (e.g., the position quantum property) can become indeterministically initiators with a probability per unit time and start an SDC. Regarding what I will call *EnDQT-MWI*, it arises from considering a theory like EnDQT, but where the generators of EnDQT don't give rise to determinate values indeterministically in a single world but instead give rise to multiple systems with determinate values deterministically, where each corresponds to a world. We could perhaps also have an *EnDQT-Hybrid* that arises from modifying the generative-Hybrid by introducing initiators in them. In EnDQT-Hybrid, for example, initiators give rise to stochastically evolving classical systems with certain quantum properties always stably differentiated. Or, we wouldn't have initiators as systems but as the events that are behind the decoupling between the classical properties (i.e., always stably differentiated quantum properties that evolve stochastically in a certain way) and the quantum ones. So, EnDQT-Hybrid would have the advantage of giving a unifying explanation for why we have both classical and quantum systems. A mechanism to describe these kinds of initiators should be explored in future work.

All four theories mentioned above could use QCMs to provide a local common explanation of Bell correlations. This is because, similarly to EnDQT, they in principle possess the following features: i) all of them appeal to common causes with indeterminate values represented via quantum states, which makes it easier to appeal to and interpret the quantum Markov condition as concerning common causes with indeterminate values; ii) they don't reify the quantum states, which doesn't lead to inferences that consider that Alice affects the space-like separated Bob and vice-versa in EPR-Bell scenarios; iii) Alice and Bob in EPR-Bell scenarios interact locally with their target systems via local DSs,[78] not influencing each other non-locally; and iv) no non-local ISs are assumed or needed like in the QTs above.[79] Notice that i)-iv) allow these theories to interpret QCMs non-instrumentally as clearly representing local features of the world, and not as hiding non-local influences *behind* quantum states and interventions on systems.

So, if quantum states concern systems with indeterminate values and the possible determinate values, as well as DSs and ISs, whether a theory obeys relativistic causality depends on the details of how the indeterminate values become determinate via ISs and DSs. So, by allowing for fundamental systems to have indeterminate value properties and not reifying the wavefunction or seeing it only as nomic, we gain the benefit of being able to add instead a different structure, which allows for locality in certain QTs. We saw that EnDQT appeals to ISs without non-local interactions and local SDCs that start with initiators as its structural generators, and above I have mentioned other possible structural generators of this kind through the hybrid EnDQT versions. Let's call the strategy that appeals to i)-iv), assuming these kinds of structural generators, the local structural generative strategy.

On the other hand, WR and PO lack this benefit. If the wavefunction is a real field, then non-local causation in spacetime seems built into its structure. The fact that PO proponents regard the wavefunction/quantum states as a law, rather than just helping to represent and infer features of systems and local DSs and ISs (like EnDQT assumes), presses one to consider that the regularities at a distance in Bell-like scenarios lead to non-local influences between events.

[78] Although one may doubt that EnDQT-collapse is local. See footnote 85.
[79] See Pipa (2023) for more details about this strategy. Future work will go into further details concerning this strategy.

Thus, via the local structural generative strategy, GQT opens new and interesting possibilities and strategies compatible with relativistic causality. Hence, GQT, in principle, provides ways of helping construct quantum theories compatible with relativistic causality. Given the importance of relativistic causality, should be regarded as an important benefit, and it’s one that these views lack.

Third, notice that not all QTs reify the wavefunction, and adopt WR (or even other related approaches), such as EnDQT, single-world relationalist theories mentioned above such as Relational Quantum Mechanics, and hybrid classical-quantum theories. Furthermore, not all QTs see the wavefunction as a law, such as at least Relational Quantum Mechanics, other single-world relationalist views, and EnDQT. Since facts are relative to some entity in single-world relationalist views, there is no way of seeing the wavefunction to govern or describe in general all those facts.[80] Furthermore, unlike the case of the PO, some QTs tend to take systems with indeterminate values/undifferentiated quantum properties either absolutely or relationally as playing an important explanatory role, such as EnDQT or Relational Quantum Mechanics, respectively. Thus, GQT has the benefit of, in principle, being an ontological framework that has a wider application, which can facilitate the comparison between QTs because we can use the same ontological framework to better compare the different QTs (more on this below).

Fourth, by not reifying wavefunctions or considering them as laws, and by allowing for certain new kinds of entities, GQT provides new and interesting ways of comparing different quantum theories and finding their advantages and disadvantages, and which ones we should prefer. I regard this as another benefit of GQT since it might help us find the correct QT, and as we will see, this way of comparing QTs cannot be done via the other ontological frameworks.

One type of new comparison that GQT allows for is at the level of generators and generative quantum properties. Despite our world being fundamentally quantum or at least mostly quantum, certain determinate values seem to arise preferably due to certain generators, and generative quantum properties. What selects the elements of this subset of determinate values, generators, and generative quantum properties? As I have argued in section 2.4, EnDQT via initiators and law-like interactions between systems that belong to SDCs can, in principle, explain this selection in a unificatory and simple way.[81] It’s simple because only one generator is in principle initially and fundamentally postulated

[80] See the paragraphs above for the reasons why EnDQT doesn’t adopt the nomological view.
[81] See Pipa (2023) for more formal details.

(modulo future developments in cosmology), the inflaton, and simple CDCs. It's unificatory because all generative quantum properties and generators trace back to this system, as well as the determinate values that the systems having them favor.

On the other hand, generative-GRW, generative-Bohmian mechanics, and generative-hybrid favor only a subset of all quantum properties as generative, and it's a brute fact why only some quantum properties among the many existing ones are generative. Also, they postulate many systems as generators (all the systems with position quantum properties).

Generative-MWI and generative-relationalist-single-world theories don't postulate fundamental generators, except generative-RQM, which considers that all systems are generators. However, contrary to EnDQT, they don't provide a unificatory explanation for why, in a wide range of interactions, specific systems are generators and others aren't, and why certain quantum properties are generative ones and others aren't. A MWI proponent might reply that what explains these features are the dynamical laws, expressed via the Hamiltonian. More precisely, these are emergent features of a collective of systems that are described/governed by certain laws concerning the quasi-classical domain. The latter involves Hamiltonians, which involve a diversity of observables. However, what selects these particular laws among the many possible ones? A MWI proponent is pressed to assume that, like there are many worlds, there are also many laws. So, in principle, there will be a large diversity of laws, governing/describing systems in different worlds. Some of those laws are likely largely different from the laws in our world. This contrasts with EnDQT, which again can provide a unificatory explanation for these laws. A MWI proponent might attempt to explain generators and generative quantum properties by appealing to the features of the environments that monitor a target system S.[82] These environments, via interactions, select a pointer observable that represents a quantum property of S that, in later interactions between S and other systems, will give rise to S having generative quantum property and S being a generator. However, then one would need to explain why the environment has those features that give rise to such selection, i.e., those generative quantum properties, and this gives rise to circularity.

One might object that EnDQT moves the brute facts concerning generators and generative quantum properties to the early universe where initiators manifested themselves. However, this is at least an explanation for them (versus a brute fact) or

[82] For example, one could be tempted to adopt the quantum Darwinist strategy (Zurek, 2009) and consider generative quantum properties as those that tend to proliferate in an environment.

arguably a more parsimonious one since, as I have mentioned above, fundamentally, we just need one special generator. Every other fact regarding generators and generative quantum properties should be explained through chains of interactions that started with the initiators. Furthermore, any QT already needs to invoke the initial conditions as a brute fact for various explanatory purposes (e.g., explain the arrow of time, solve the problems that inflation pertains to solve, etc.). EnDQT at least has the advantage of being able to ground the different already appealed brute facts in a more fundamental one, which concerns the initial state of initiators. However, note that there is a sense that this can be an explanation for the initial conditions of the universe because non-fundamental *special* facts about the initial conditions of the universe can be grounded on the more fundamental *special* facts about QT. This is because initiators as special entities, and the phenomena that they give rise to, are fundamental for QT according to EnDQT.[83]

Another type of new comparison that GQT allows for is at the level of the determination and indetermination structures appealed by each QT. EnDQT, via initiators and local interactions between systems, explains the local structure of SDCs in a unified and non-relational way. The ISs and/or DSs of other quantum theories, except generative-single-world-relationalist theories and generative-local-MWI, have a more complicated non-local structure (e.g., they postulate UDIs, destruction interactions, etc.), potentially conflicting with relativity.

Furthermore, generative-single-world-relationalist theories and the generative-local-MWI offer us DSs that don't causally connect "distantly separated" systems or worlds (if a notion of distance even makes sense for these views) in the sense of worlds or systems that don't share the same environment. This threatens the power of their explanatory resources since certain local phenomena are more plausible to explain if they are due to certain "distant" systems or worlds. I am not just referring to Bell correlations here, but whatever is happening with systems that are not connected with certain DSs, although it's plausible and simpler to consider that they end up influencing the systems that belong to them.

For example, in the case of generative-single-world-relationalists (such as RQM), the classical/determinate behavior of the sun or even the moon before they influence systems on Earth. However, the values of the sun or the moon would be relationally indeterminate for these systems.

[83] See Pipa (2023) for more details on these virtues.

In the case of generative-local-MWI, the threat comes from the events that are happening in some worlds that seem to influence other worlds (e.g., the different branches concerning whatever is possibly happening to my family in the other continent that seem to end up influencing my branches). However, unlike generative-global-MWI, which connects different systems within a world via DSs, due to the ever-present unconnected branching, we don't have a way to track or even make sense of how different branches causally connect.[84] Let's consider that if theory T1 is more parsimonious, less problematic, and more explanatory than theories T2, then theory T1 should be preferred to T2. Assuming this, I think that if we consider the above reasons of locality, parsimony, and explanatory power, we should prefer EnDQT to the above theories. GQT makes those reasons manifest.[85]

Thus, by not reifying wavefunctions or considering them as laws and by allowing for new entities, GQT provides new and interesting ways of comparing different quantum theories, finding their advantages and disadvantages, and deciding which ones to prefer. I regard this as another benefit of GQT since it might help us find the correct QT.

However, we might not take the above comparison seriously and object that the preference for EnDQT regarding the above features, when we compare it with other QTs, disappears when we adopt an ontology that views the wavefunction like WR or PO. These QTs can postulate the existence of the wavefunction of the universe either as a fundamental law or field, which provides a simpler and unificatory explanation for why certain systems are generators and others not, why certain quantum properties are generative and others aren't, and why certain structures exist. On top of that, one may even dismiss GQT because it's an ontological framework that gives, in a sense, an uncharitable treatment of some QTs that were built under the assumption that we should reify the wavefunction in some sense. However, I think the above comparison should be taken seriously, as well as GQT as a good ontological framework for QT.

[84] A tension is found in the MWI theories between allowing for more explanatory power via a generative-global-MWI view and allowing for more locality via a generative-local-MWI or arguably a generative-quasi-local-MWI view.

[85] What about if we compare EnDQT with the hybrid views presented above? We would have to examine other costs of these theories. In the case of EnDQT-MWI, contrary to EnDQT, it will have an additional problem of probabilities plaguing the MWI, which can still make it an undesirable view, and it will have the same explanatory power deficits identified above that the local-MWI has. Note that due to its determinism and reversibility of quantum states, EnDQT-MWI is a theory different from EnDQT. In the case of EnDQT-collapse, in so far it would be empirically satisfactory, contrary to EnDQT, it will still involve the cost of modifying the fundamental equations of QT to account for the postulated probability per unit time of a system becoming an initiator. Also, it's unclear if this version is really local because the probability per unit time of a system becoming an initiator would be specified relative to a preferred reference frame. In the case of EnDQT-Hybrid, it's still unclear what would constitute its initiators or events mentioned above and whether gravity should be treated as a separate field that shouldn't be quantized.

First, I think that multiple issues regarding the different QTs manifest in similar ways when they adopt WR or the PO. The appeal to brute facts about primitive ontologies or the existence many laws in the MWI are still there when these QTs adopt these ontological frameworks. The non-locality at level of spacetime too, as well as the above issues with single-world-relationalist theories and the local-MWI. GQT just makes these features more manifest.

Furthermore, as I also mentioned, GQT, in principle, facilitates and improves the comparison between QTs because it can be applied more widely while using the same kind of ontology. So, it's plausible to consider that GQT can provide a more charitable treatment of QTs in general than these other two frameworks. Furthermore, given the current state of the foundations of physics, where we are still trying to unify QT with general relativity and solve the measurement problem, I think that we should consider that the general applicability and comparison between QTs that GQT allows for is epistemically more valuable than the restricted applicability that PO and WR tend to lead to. This is because it might allow for progress by offering new means to evaluate in general different QTs.

Even if one insists on the simplicity of the wavefunction/quantum states, these objects aren't necessarily simpler than DSs and ISs by many measures of simplicity. For instance, the relations of influence that they permit, which these ontologies take seriously, are very diverse and subject to multiple precisifications, not necessarily simplifying them. Just look at the different QTs, as well as subversions of them. For instance, just within the MWI, Sebens & Carroll (2018) make the distinction between local and global branching as one way of precisifying what these objects represent and the relations of influence that they allow for. Also, these objects per se permit complicated nomic relations, actions at a distance, and/or evolutions within spaces of many dimensions. Furthermore, since we have a redundancy in the global phase,[86] many different wavefunctions/quantum states seem to be able to give rise to/govern/describe the *same* physical state of the systems, and so in this aspect, these ontologies seem to complexify even more the description of these relations of influence because there are too many possibilities. So, given the above reasons, DSs and ISs don't necessarily give rise to more complicated relations of influence than the wavefunction/quantum states.

[86] As said previously, given the inferential role of quantum states assumed by GQT, we can ignore the global phases of quantum states to make inferences about and represent properties of systems.

On top of this complexity, PO and WR have epistemic issues that GQT doesn't have. Let's suppose we attempt to answer the question regarding how we know and why we have *this* wavefunction of the universe and not another, where this wavefunction accounts for the behavior of quantum systems. The answer to this question will hardly be satisfactory because wavefunctions aren't directly observable and do not easily connect with our familiar world or nomic standards. On the other hand, GQT appeals to, in principle, at least more familiar or standard entities: systems and their interactions; and a more familiar and standard view of quantum states to physicists, i.e., mostly as predictors and inferential tools. Also, many physicists are used to thinking about indeterminacy via the EEL (section 1). These standard and familiar assumptions will likely lead GQT to be considered overall more satisfactory than PO and WR.

Also, as I have mentioned, unlike GQT, these ontologies give rise to potentially problematic unexplained non-local influences (PO with its nomic view),[87] a revisionist attitude towards laws (PO), or the problem of making sense of the three-dimensional space manifest image (WR), which gives rise to further issues when comparing the different views. So, given this reason and the ones explained in the two previous paragraphs, I think that the above unificatory explanation based on the wavefunction is more problematic and not necessarily simpler.

Thus, since GQT provides the above benefits that these influential frameworks don't offer, including having wider applicability without the costs mentioned above, which include getting rid of what can be seen as problematic distractions associated with reifying the wavefunction or viewing it as nomic, I think it's a good ontology to compare different QTs and for QT. Moreover, I also think that GQT and the above comparison between QTs should be taken seriously.

4. Conclusion and future directions

I have presented Generative Quantum Theory as a new ontology for quantum theories and shown how it can be implemented via GRW, the MWI and single-world relationalist views, Bohmian Mechanics, hybrid classical-quantum theories, and EnDQT. I have also distinguished it from the most discussed ontologies for quantum theories,

[87] Whereas WR and GQT appeal to certain entities.

namely, wavefunction realism and primitive ontology, and argued that it has certain benefits that they lack without some of their costs, such as non-locality.

Furthermore, I have presented generative quantum theories that adopt a property ontology based on quantum properties, which also allowed for a new analysis of quantum indeterminacy and determinacy. However, other generative theories are possible for other kinds of property ontologies. Future work should explore whether it's beneficial to build generative theories that use another account of properties, such as determinable-determinates,[88] etc.

Also, it should explore applying this framework to other QTs, such as superdeterministic, retrocausal,[89] and other relationalist theories, as well as to different pictures of QT. Relatedly, it should analyze other possible generators (structural and non-structural) and initiators (a sub-kind of generators used by EnDQT and hybrids). This could allow us to generate further new quantum theories. Also, it should extend this view to Quantum Field Theory (although, see section 4). Furthermore, it should compare GQT with other ontological frameworks that weren't discussed here. I suspect that GQT will provide many benefits that they don't have without their costs, given the distinctiveness of GQT and since in different ways most of the other ontological frameworks reify the wavefunction or the quantum state, or see it as a law.

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[88] Calosi & Wilson (2019). Briefly, for example, in this property ontology, we would view observables as representing determinables (e.g., position, momentum, energy, etc.) and determinate values as representing determinates of those determinables. Interactions give rise to a determinable with a determinate. Systems would be considered as collections of determinables, which at different moments of time, have determinates or not (e.g., having a spin-x with or without a determinate of spin-x) depending on their interactions like in the gappy version of quantum indeterminacy presented in Calosi & Wilson (2019). Quantum indeterminacy arises when we have state of affairs constituted by a system lacking a determinate of a determinable.

[89] See, e.g., Hossenfelder & Palmer (2020) and Friederich & Evans (2019).

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